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## Monterey, California



FY 74 EXPERIMENTAL HYDRAULIC RAM STUDIES

H. L. POWER

August 1974

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NAVAL POSTGRADUATE SCHOOL  
Monterey, California

Rear Admiral I. W. Linder  
Superintendent

Jack R. Borsting  
Provost

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## I. INTRODUCTION

In recent years the study of non-nuclear vulnerability and survivability of aircraft flying in a hostile arena has become increasingly important. Increased aircraft sophistication has brought about increased complexity of aircraft systems. Better surface-to-air defenses, high weapon system costs and decreasing defense budgets have made survivability analysis and design absolutely necessary.

Aircraft fuel cells are very susceptible to damage because they have the largest surface area and volume of all vulnerable aircraft components. Ballistic threats have caused extensive fuel cell structural damage which can result in fuel starvation, fires or explosion. Major fuel cell structural damage cannot be tolerated in the case of "wet wing" aircraft for obvious reasons. It is for these reasons that the study of the failure mechanisms of fuel cells must be understood so that survivable designs may be evolved.

Projectiles which penetrate fluid filled cells cause damage many times more severe than that incurred by impact with an empty cell. This interaction of fluid filled cells with projectiles is called hydraulic ram. The exact nature and extent of damage can be related to projectile energy loss in each of five phases of hydraulic ram. These phases are usually identified by the dominant energy transfer mechanism presented.

The first phase involves projectile penetration through the entry wall material. During this entry phase projectile energy is lost by "punching" a hole in the entry wall material. If the projectile is not tumbling and strikes normal to the entry wall the damage size is approximately equal to the maximum cross sectional area of the threat. Tumbling and incident strikes can produce larger damage sizes and

correspondingly higher penetration energy loss.

If sufficient projectile energy is available the threat protrudes from the back side of the entry wall and subsequent fluid displacement produces a strong hemispherical shock wave which propagates into the tank fluid. This shock phase of hydraulic ram generates intense pressure loadings on the entry wall but because of spatial attenuation these loadings are localized to the immediate area surrounding the impact point. If the wall is thin, and the threat kinetic energy is large, or if during the penetration phase the entry wall has been severely cracked, shock phase pressure loadings can cause extensive damage to the entry wall area.

As the projectile travels through the tank fluid a cylindrical cavity is formed. The cavity is a result of a radial velocity imparted to the fluid by the projectile motion. Inside this cavity are trapped air, which entered during penetration, and fluid vapor. Projectile form drag dissipates projectile energy in this drag phase of hydraulic ram.

If the fuel cell has a depth which is less than the distance required for the drag phase to dissipate all projectile energy (for example the case of a projectile penetrating a "wet wing" from the lower surface) an exit phase of hydraulic ram exists. The exit phase involves exit wall pressure loadings due to projectile wall proximity and due to fluid motion toward the wall that has been established by the earlier phases. These loadings usually cause extensive, large scale damage to the exit wall.

The last phase is produced when the drag phase cavity growth is halted by fluid pressures due to the tank boundaries. The cylindrical

cavity changes to a spherical shape and collapses. Collapse compresses the trapped cavity vapors to a high pressure resulting in a re-expansion of the cavity. Expansion and collapse is repeated several times before the stored energy is dissipated. The resulting fluid pressures can cause large side wall loadings which can further damage the cell. These oscillatory cavity phase pressures can destroy large depth cells. The cavity phase is also responsible for pumping tank fluid out damaged areas of small depth tanks. This release of fuel, atomized by wall cracks and petaling, creates an extreme fire hazard.

All phases of hydraulic ram must be considered when designing "ram proof" fuel cells. Fuel cell damage and the dominant hydraulic ram failure mechanism are dependent upon the aircraft mission (which determines the path, energy level and size of the most probable threat) and the geometry of the fuel cell (size, location, and construction). For example, if the tank wall construction is "thin" and the threat energy is "high" the shock phase of hydraulic ram can cause catastrophic damage of the entry wall. Tanks with "small" depth are very susceptible to damage produced during the exit phase of hydraulic ram while the cavity phase contributes only minor additional structural damage. Fuselage tanks may have dimensions sufficient to eliminate the exit wall phase. The primary ram damage component is the cavity phase in this case. Efficient fuel cell protection must be tailored to the dominant ram components. Since ram damage is configuration dependent extensive vulnerability testing will be required to substantiate the defeat of a given threat.

This report presents the results of experimental studies conducted at the Naval Postgraduate School to understand the basic phenomena

associated with the first three phases of hydraulic ram.

## II. PENETRATION PHASE OF HYDRAULIC RAM

The assessment of ram damage to any fuel cell can be related to the energy dissipated in each of the five phases of hydraulic ram. For this reason it is necessary to be able to predict the projectile energy loss during entry wall penetration. In general this energy loss is a function of wall parameters and projectile initial energy, obliquity, material properties, tumbling and shape. For the purposes of supporting NPS experimental studies of the shock and drag phases of hydraulic ram, it was necessary to be able to predict the penetration energy requirements of untumbled, copper-jacketed, small arms lead projectiles with various masses and nose shapes when impacting normal to 7075-T6 aluminum tank entry walls of various thicknesses.

Dunn's<sup>1</sup> theory for hypervelocity ballistic impact problems assumes that "there exists in each unconstrained material body at constant uniform temperature a dynamic yield strength,  $\sigma_y$ , that is a constant of the material." This dynamic yield strength when multiplied by the resisting cross sectional area of the projectile gives an estimate of the instantaneous retarding force during penetration. The projectile equation of motion

$$\ddot{x} + \frac{\sigma_y}{m} A(x) = 0 \quad (\text{II-1})$$

may then be solved to yield the time history of penetration depth and projectile velocity assuming that the dynamic yield stress of the projectile is greater than that of the entry wall. The work done during deceleration yields an estimate of the kinetic energy loss during penetration. For the retarding force postulated, the work done is equal to the product of the dynamic yield stress and the volume of entry wall material swept out by the penetration. The theory, therefore,

predicts that the penetration energy loss is independent of projectile shape. The minimum initial projectile velocity  $V_i$  which will penetrate the entry wall is called the ballistic limit and is given by:

$$V_o = \sqrt{\frac{2\sigma_y At}{m}} \quad (\text{II-2})$$

where A is the damage area and t is the entry wall thickness.

The exit velocity  $V_e$  of the projectile penetrating a given wall thickness is given by:

$$V_e = V_o \sqrt{\left(\frac{V_i}{V_o}\right)^2 - 1} \quad (\text{II-3})$$

The corresponding percentage energy loss is given by:

$$\%E_{\text{Lost}} = \frac{E_i - E_o}{E_i} = \frac{200\sigma_y At}{m} \left(\frac{1}{V_i^2}\right) \quad (\text{II-4})$$

Experimental studies conducted by Dunn suggest that the correct value of  $\sigma_y$  is approximately fifteen times the shear modulus of the entry wall.

These theoretical predictions were compared to a series of experiments<sup>2</sup> in which projectile shape, impact velocity, and mass were varied. The tank entry wall was simulated by a 7075-T6 Aluminum plate of thickness 0.05, 0.09, or 0.16 inches. Three projectile nose shapes ranging from hemispherical to a 1.6 fineness ratio ogive were tested. Figure II-1 shows the components of the ballistic range used for these experiments. The rifle mount shown in Figure II-2 was adjustable in azimuth and elevation and was designed to hold rifles up to and including 30 caliber. The impact velocity was measured by using three chronograph screens mounted in front of the test plate. Each screen had a five volt D.C. source across it. When the screen was broken by the passage of the

bullet the circuitry shown in Figure II-3 shaped the pulse and started or stopped a Monsanto 101B 1MHz counter. Time interval between screens was converted to projectile average velocity to determine the initial velocity. A similar pair of chronograph screens were mounted behind the test plate to measure the exit velocity. Figure II-4 shows a typical chronograph station.

Early in the test phase it was experimentally determined that the size and method of supporting the test plate had no significant effect on the exit velocity. It is expected therefore, that the exit velocity for hypervelocity impact would be insensitive to wall-fluid foundation effects that would be present in any fluid filled fuel cell. Several rounds were fired through a single 18-inch square plate and the resulting exit velocities were identical even if the point of impact was as close as two times the damage diameter away from any previous damage. All further shots used a three by four inch test plate to simulate the fuel tank entry wall. Figure II-5 shows the experimental apparatus.

Spark shadowgraphs of the penetration were also taken. The delay circuitry shown in Figure II-3 was used to trigger the spark source just after the penetration. Figure II-6 shows the optical setup. The light from the spark source was directed to a film plate by a concave mirror on the opposite wall. The collimated light then passed behind the test plate and onto the film plate. These shadowgraphs showed that, except for minor distortion of the nose tip, that these copper-jacketed lead projectiles show no appreciable deformation during the penetration. Figure II-7 shows a typical shadowgraph. The yield strength of copper is approximately  $0.39 \times 10^6$  psi as compared to

$0.25 \times 10^6$  psi for Aluminum. The theory assumes that the yield strength of the projectile is significantly larger than that of the entry wall. Since these data show that projectile shape was unchanged it can be concluded that the assumption only need be made that the yield strengths of the projectile is equal to or greater than that of the entry wall for hypervelocity impact problems.

Figure II-8 shows a comparison of experimental impact and exit velocities with the theory for a 45 grain 22.2 caliber projectile impacting plates of various thicknesses. Projectile nose shape was found to have no effect on the results; therefore, no differentiation between shapes has been made on this figure. It is obvious that equations II-2 and II-3 predict very accurately the exit velocity for hyperballistic impact. Figure II-9 shows the resulting penetration energy comparison. Good agreement with the prediction equation II-4 is obtained. Additional shots with bullet masses as large as 63 grains have shown similar excellent agreement with theory.

The independence of penetration energy loss with projectile shape makes it possible to extend these results to many cases of interest to the fuel cell designer. It could be expected, for example, that the penetration energy of warhead fragments impacting normal to any intervening structure and the fuel cell wall can be predicted accurately using this simple theory.

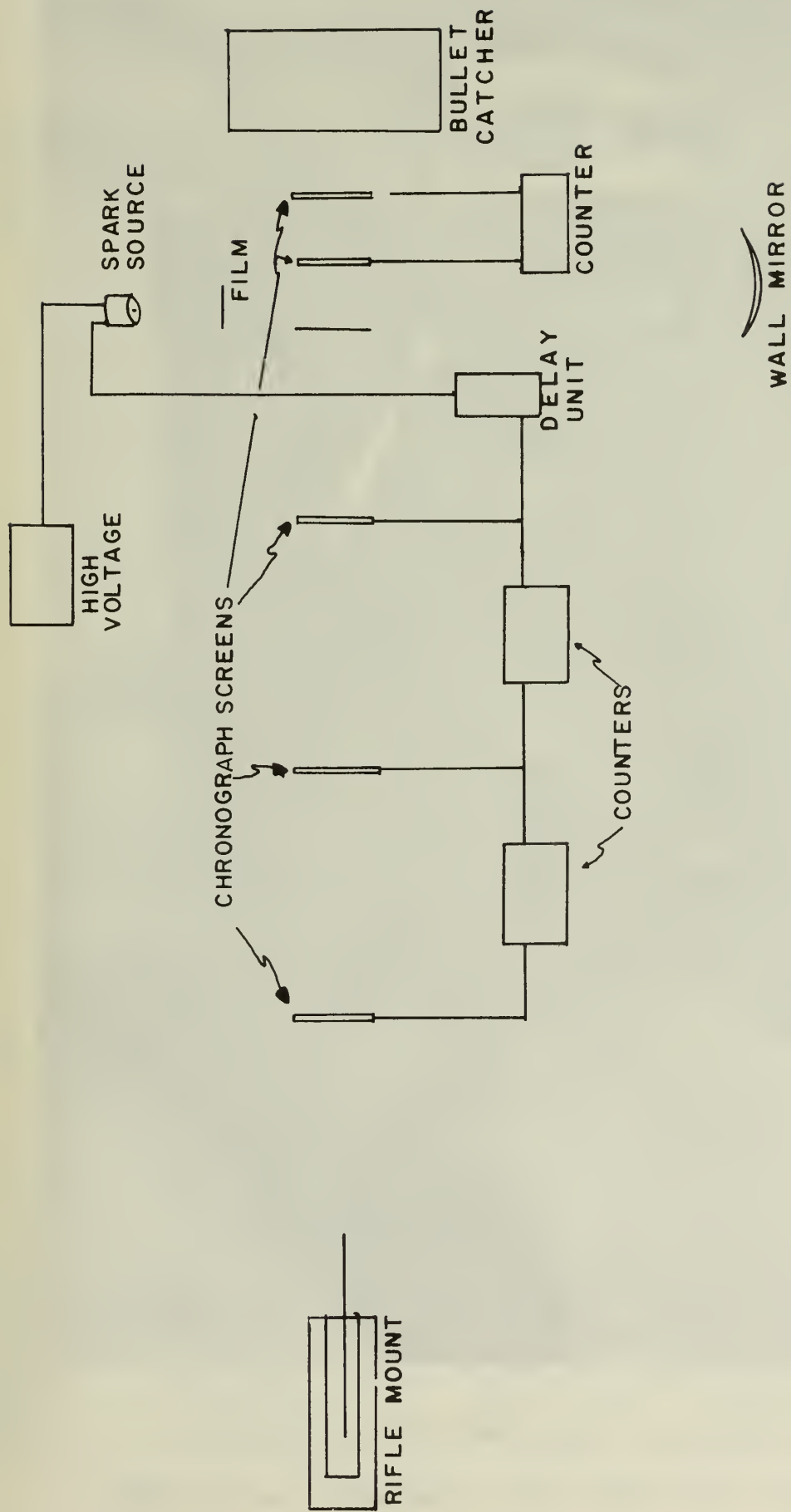


FIGURE II-1. Ballistic Range Components.



FIGURE II-2. Ballistic Range Rifle Mounting System.

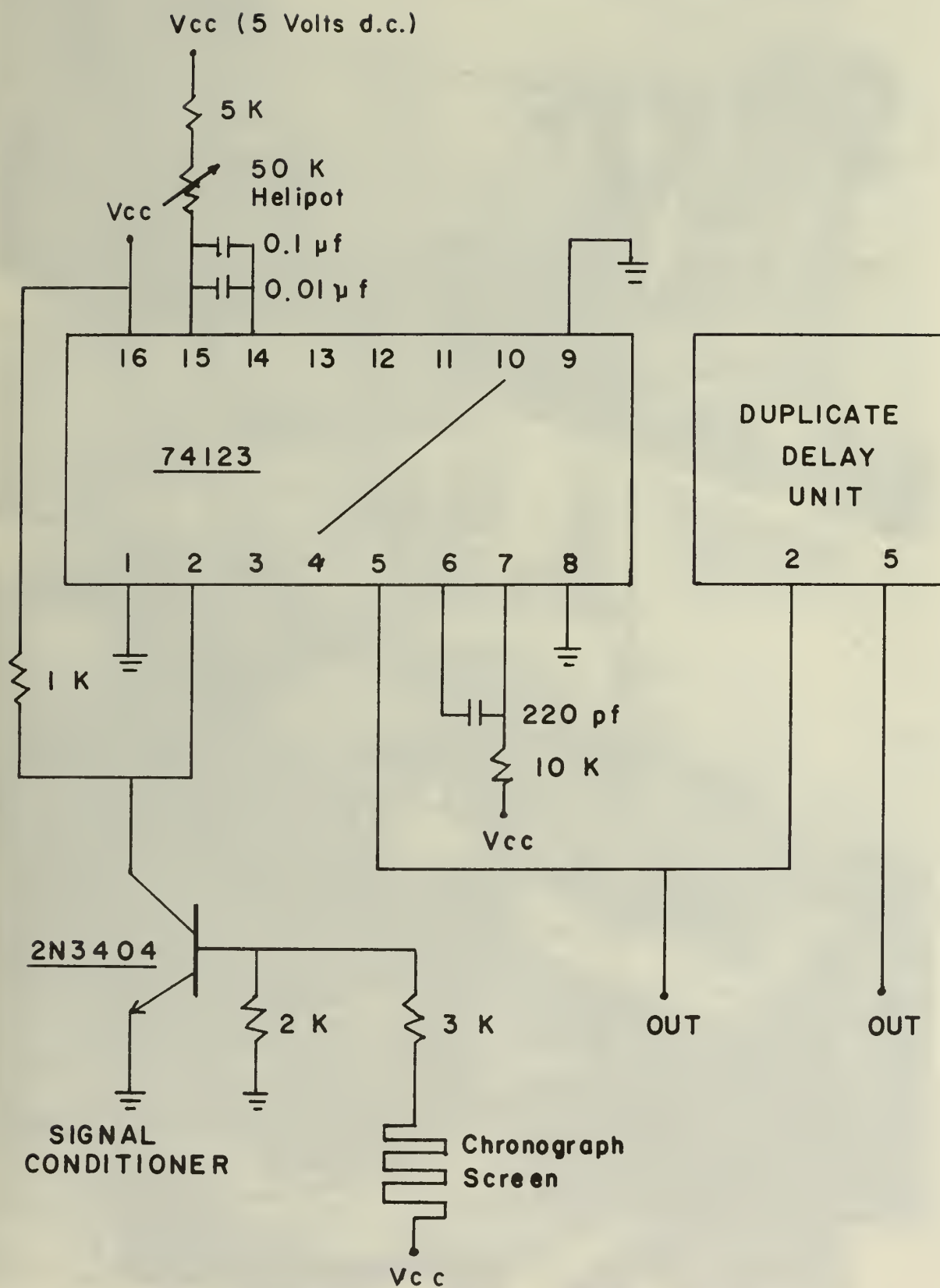


FIGURE II-3. Adjustable Time Delay Unit Circuitry

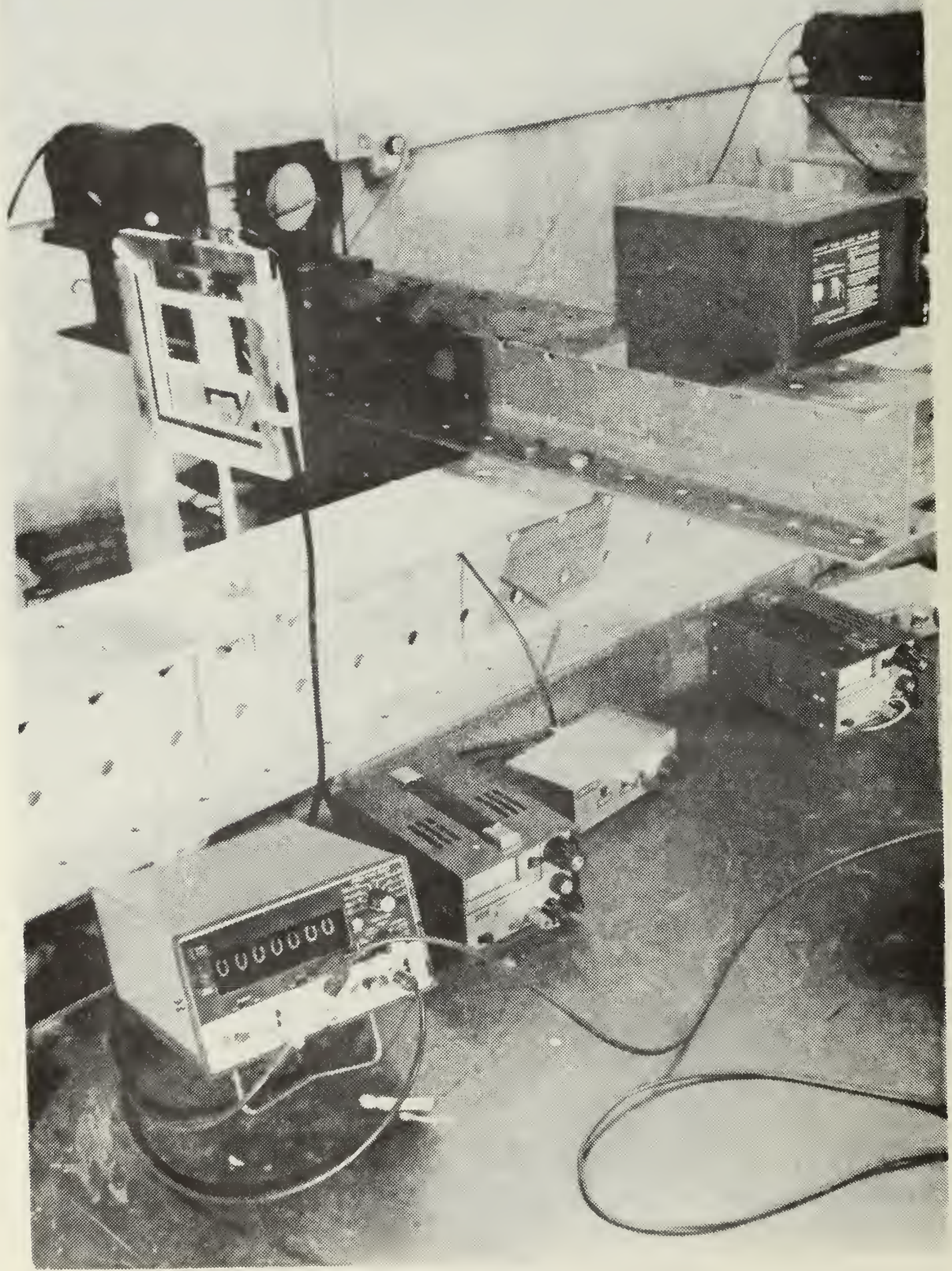


FIGURE II-4. Ballistic Range Chronograph Station



FIGURE II-5. Test Plate and Chronograph Station



FIGURE II-6. Spark Source and Mirror

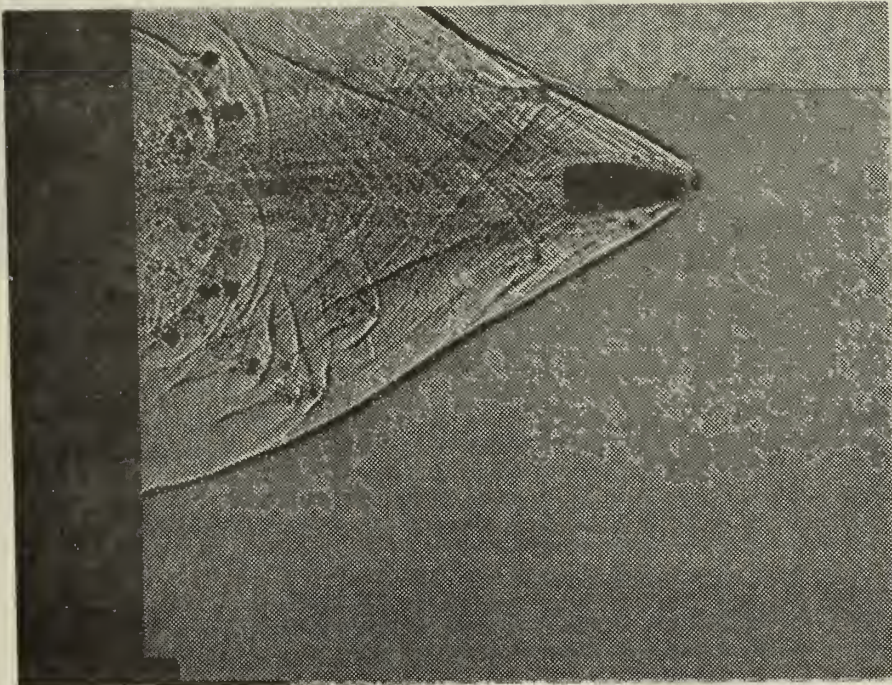
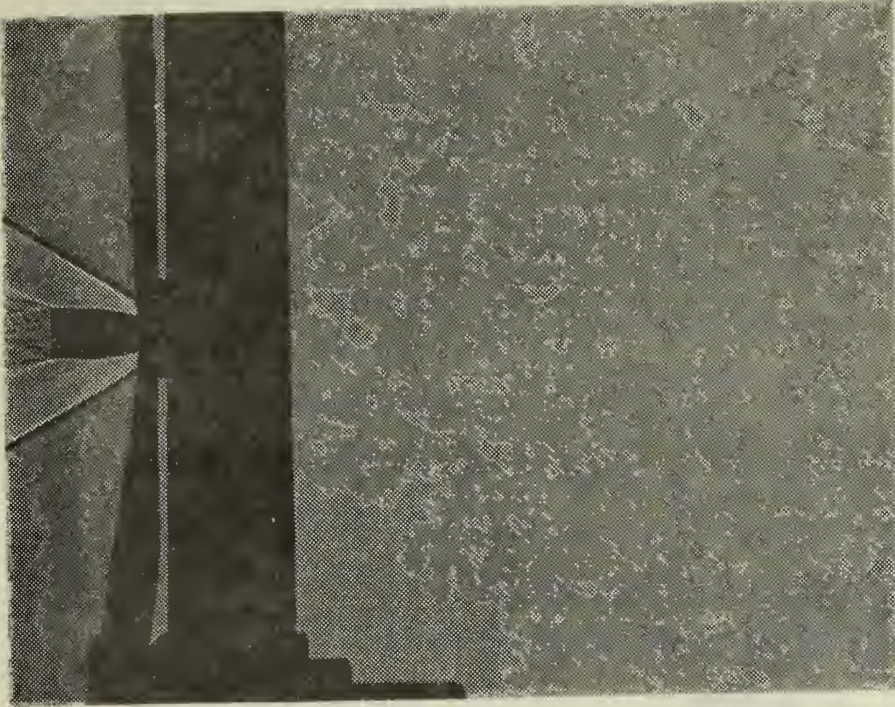


FIGURE II-7. 45 Grain Spitzer Entering and Exiting Aluminum Plate

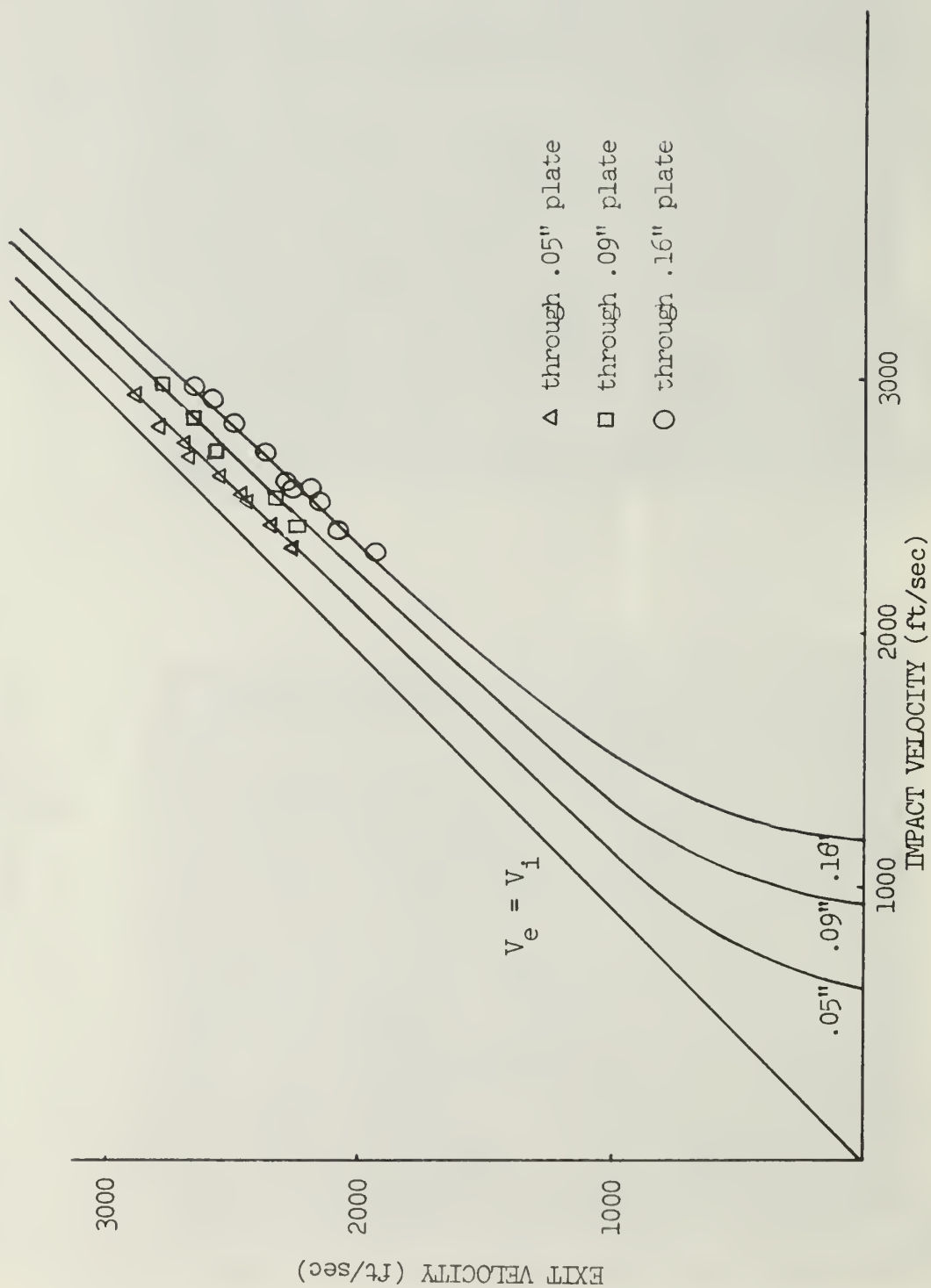


FIGURE II-8. Impact Velocity vs. Exit Velocity for Plates of Three Thicknesses

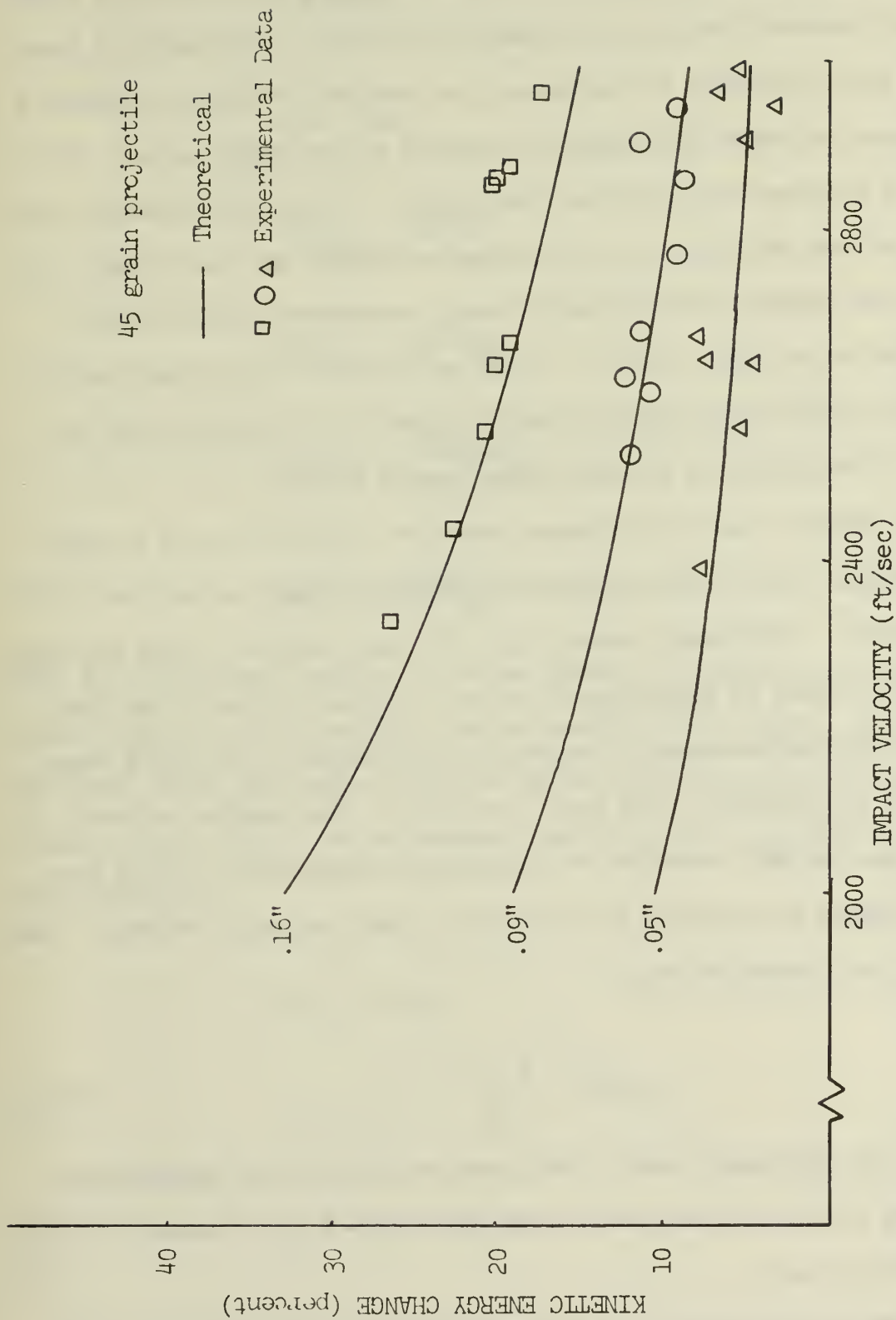


FIGURE II-9. Impact Velocity vs. Percent Kinetic Energy Loss for Aluminum Plates of Three Thicknesses

### III. Shock Phase of Hydraulic Ram

In order to predict fuel cell damage due to the shock phase of hydraulic ram it is necessary to relate the change in projectile energy to wall pressure loading. The results of several investigators<sup>3</sup> have shown that protrusion of the projectile into the tank fluid produces a hemispherical shock wave which is centered at the impact point. Projectile momentum and path after entry have no observable effect on the shape of this shock wave as it propagates through the tank fluid. In fact, even impacts with obliquity show a hemispherical shock front centered at the impact point. It may be concluded from these results that the shock characteristics may be predicted by assuming that the shock is the result of a point energy source release.

To predict fuel cell internal pressures created by such an event the computer code in the Appendix was developed based on the theory of Yurkovitch<sup>5</sup>. The theory assumes that the tank walls are rigid and that the shock radius is proportional to the 0.8 power of time. The one-dimensional Rankine-Hugoniot equations are coupled to the fluid state equation to determine shock front conditions. The equation of state is based upon the Tait equation for isothermal compressible liquids when fluid changes are produced by an adiabatic and isentropic process. The assumed state equation was:

$$p = \frac{\rho_o C_o^2}{n} \left[ \left( \frac{\rho}{\rho_o} \right)^n - 1 \right] \quad (\text{III-1})$$

where  $\rho_o$  is the density and  $C_o$  the speed of sound in the undisturbed fluid and  $n$  is a constant for a given fluid ( $n = 7.0$  for water,  $n = 10.6$  for aviation fuel).

Nondimensionalization of the variables was accomplished by the

following scheme:

$$\xi = \frac{r}{R_s(t)}$$

$$M_s = \frac{\dot{R}_s(t)}{C_o}$$

$$\psi(\xi, M_s) = \frac{\rho(r, t)}{\rho_o}$$

$$\phi(\xi, M_s) = \frac{u(r, t)}{R_s(t)} \quad (\text{III-2})$$

$$f(\xi, M_s) = \frac{p(r, t)}{\rho_o R_s^2(t)}$$

$$g(\xi, M_s) = \frac{e(r, t)}{R_s^2(t)}$$

where  $R_s$  is the shock radius,  $u$  is the particle velocity,  $p$  is the pressure and  $e$  is the specific internal energy of the fluid. By using the strong shock assumptions that the shock front pressure and energy are much greater than the undisturbed conditions the equations of motion reduce to:

$$1 = \psi_1 (1 - \phi_1)$$

$$f_1 = \phi_1$$

$$g_1 = \frac{1}{2} f_1 \left( 1 - \frac{1}{\psi_1} \right) \quad (\text{III-3})$$

$$f = \frac{1}{n M_s^2} (\psi_1^n - 1)$$

Solving for the conditions at the shock front

$$\psi_1 = \frac{1}{1 - \frac{1}{nM_s^2} (\psi_1^n - 1)}$$

$$\phi = \frac{1}{nM_s^2} (\psi_1^n - 1) \quad (\text{III-4})$$

$$f_1 = \phi_1$$

and assuming values of  $\psi_1$  the set III-4 can be solved for  $M_s$ ,  $f_1$  and  $\phi_1$  respectively. The shock front fluid parameters are now known as a function of the shock Mach number,  $M_s$ , but their distribution behind the front was to be determined.

The distribution of the flow parameters behind the shock is based on the assumption that the density profile is given by

$$\psi = \psi_1 \xi^{q(M_s)} \quad (\text{III-5})$$

The exponent  $q(M_s)$  is determined by equating the total mass enclosed by the shock

$$\rho_0 R_s^3 2\pi \int_0^1 \psi \xi^2 d\xi \quad (\text{III-6})$$

to the original mass occupied by the enclosed volume

$$\frac{2\pi R_s^3 \rho_0}{3} \quad (\text{III-7})$$

with the result

$$\int_0^1 \psi \xi^2 d\xi = \frac{1}{3} \quad (\text{III-8})$$

Substitution of (III-5) into (III-8) yields

$$q(M_s) = 3 (\psi_1 - 1) \quad (\text{III-9})$$

the nondimensional particle velocity  $\phi$  was calculated by substituting the density profile into the continuity equation

$$(\phi - \xi) \frac{\partial \psi}{\partial \xi} + \psi \frac{\partial \phi}{\partial \psi} + 2 \frac{\phi \psi}{\xi} = - \beta M_s \frac{\partial \psi}{\partial M_s} \quad (\text{III-10})$$

where  $\beta$  is the decay coefficient given by  $R_s R_s / R_s^2$ . The resulting particle velocity was

$$\phi = \phi_1 \xi \quad (\text{III-11})$$

The known particle velocity and density distributions were then substituted into the momentum equation

$$f = f_1 - \frac{\psi_1}{q+2} (\xi^{q+2} - 1) \left[ \frac{\phi_1}{\psi_1} - \beta (\phi_1 + M_s \frac{\partial \phi}{\partial M_s}) \right] \quad (\text{III-12})$$

to solve for the pressure distribution. The decay coefficient was determined by assuming that the shock radius is given by

$$R_s = Ct^{0.8} \quad (\text{III-13})$$

The shock Mach number was determined from energy considerations. The energy imparted to the fluid in the shock phase,  $E_o$ , is given by

$$E_o = \int_0^{R_s} (e - e_o + \frac{u}{2}) \rho_4 \pi r^2 dr \quad (\text{III-14})$$

Using the normal strong shock assumptions and the previously derived density and particle velocity distribution equation III-14 becomes

$$E_o = \pi \rho_o C_o^2 R_s^3 M_s^2 \int_0^1 \left\{ \frac{1}{n M_s^2} (\psi_1^n - 1) \phi_1 + \phi_1^2 \xi^2 \right\} \psi_1 \xi^{q+2} d\xi \quad (\text{III-15})$$

By choosing  $M_s$  the dependent variables  $\phi_1$  and  $\psi_1$  are known and equation III-15 can be integrated to yield  $2E_o/R_s^3$  versus Mach number. Given the shock phase energy release  $E_o$  it is then possible to determine the shock Mach number as a function of shock radius. There is, however, an anomaly at a shock radius of zero. To avoid a finite energy in zero volume reference 6 suggests that the initial radius be given as

$$R_o = \left[ \frac{E_o}{2\pi\rho_o C_o^2} \right]^{1/3} \quad (\text{III-16})$$

A series of experiments<sup>7</sup> were conducted to substantiate the theoretical propagation speed of the shock wave in a water filled tank. Figure III-1 shows the ballistic range components used for these tests. Projectile impact kinetic energy was measured using three chronograph screens which triggered counters. The time interval between screens was converted to average velocity and then to impact energy. A fourth chronograph screen was mounted ahead of the test tank entry wall. This screen provided a reference pulse for timing events during the shock phase. The circuitry in Figure II-3 was used to trigger a pair of spark sources at preset times after the reference pulse. In this manner, a pair of spark shadowgraphs of the events during the shock phase was obtained. Figure III-2 shows the optical arrangement of the shadowgraph apparatus.

Figure III-3 shows the test tank and stand. The fuel cell was approximately cubical with 17 inch inside dimensions. The front and back wall support plates were machined one inch thick aluminum. These plates had a 15 inch diameter circular cut-out. The simulated fuel cell entry and exit walls were mounted inside these plates with 16

equally spaced bolts. The entry wall was a .090 inch thick 7075-T6 aluminum sheet with a prepunched entry hole as shown in Figure III-4. The top of the tank was open and tape was used to prevent water leakage before impact. The side and bottom walls of the tank were one inch thick Plexiglass on which a reference grid was scribed.

The experiments were conducted at three initial projectile energy levels. Figures III-5 and III-6 show the 22 caliber projectile shapes and energy parameters. By varying the preset time delay shadowgraphs of the shock radius versus time were taken. Figure III-7 shows typical shadowgraphs. The times shown in this figure are after wall impact. The hemispherical shock centered at the impact point is readily apparent. The projectile is obscured by light refraction caused by the large density gradients produced in the stagnation region of the flow. McMillian<sup>3</sup> has shown, using X-ray shadowgrams, that the illuminated cusp can be used to determine the location of the projectile. Also apparent in the later time shadowgraph is the cylindrical cavity caused by flow separation from the projectile surface. It should also be noted that these shadowgraphs show that the shock strength (as indicated by the band width) is not uniform. The strength is a maximum directly ahead of the projectile with a weakening as the wall is approached. This effect was probably due to projectile forward motion and entry wall motion in response to the shock pressure loadings.

Figure III-8 through III-10 show a comparison of the experimental results with the theory. The data for an impact energy of 1600 in-lb shows excellent agreement with the theory assumption that the shock radius varies with the 0.8 power of time. The higher energy level data show, however, that the shock radius varies as 0.9 power of time. This

may be due to the differences in projectile shape. If the projectile is considered to be a piston in the early stages of the shock formation, the rate of change of fluid volume displaced by the piston determines the momentum exchange between the piston and the fluid, hence the shock strength. The low energy projectile had a nose shape that was more blunt than the higher energy projectiles. It is reasonable to conclude therefore, that the greater rate of change of fluid volume is displaced by the blunt projectile producing a stronger shock. The 0.8 power law has been experimentally verified by Stepka<sup>4</sup> for the case of spherical projectiles. The present data shows that this law may be extended to the case of blunt projectiles or possibly warhead fragments. The data also indicates that a 0.9 power law more closely predicts the shock propagation characteristics for projectiles with nose shapes that approximate an ogive.

Also shown in Figure III-10 (X symbols) are data for the case of projectile penetration through a solid 0.043 inch thick 6061-T6 aluminum entry wall. These limited results show that the shock propagation speed is relatively insensitive to the entry wall penetration process. The spark shadowgraphs in Figure III-11 show, however, that the solid wall shock phase wave system is considerably more complex than the prepunched case. Entry wall motion in response to the penetration phase produces a weak wave system with the shape of a truncated cone which intersects the main shock tangentially. The base dimension of this weaker shock was found to be approximately equal to the product of the speed of sound in aluminum and time. The primary shock radius, however, was found to be approximately equal to that of the prepunched wall case. The resulting wave interactions completely obscure the projectile in

this case and presumably alter the wall pressure loadings during the shock phase. Figures III-12 through 14 show the damage resulting from this type of test. These figures show that although insufficient energy was available to cause entry wall catastrophic failure, considerable plastic deformation and buckling occurred. Since the exit wall exhibited no damage, it is reasonable to assume that the entry wall damage was due to shock phase loadings with minor contributions due to loadings produced by the latter phases of hydraulic ram.

Implicit in the Yurkovitch solution for shock phase pressure loadings is a knowledge of the energy input  $E_0$ . An analytical expression for this energy as a function of projectile, wall, and fluid characteristics is not available. In addition, the motion of the thin fuel cell walls in response to these impressed pressures will reduce the fluid pressure in the vicinity of the wall. An estimate of these effects is one of the ultimate goals of the present NPS hydraulic ram research effort.

If, in the design effort to build shock phase survivable fuel cells, the most conservative approach is assumed (all of the projectile energy is lost and the walls are rigid) the solution of Yurkovitch can yield entry wall pressure loadings until such a time that the shock wave reflects from any other tank wall. Figures III-15 through III-21 show such calculated pressure profiles for the three energy levels of the previous experimental data. Figures III-15, 16, 18 and 20 show the predicted pressure signals that would exist at a constant radial position verses time. These figures show that the shock strength is quickly attenuated spatially. It is expected, therefore, that shock phase damage would be limited to the immediate area surrounding the impact

point. Figure III-22 shows the shock radius and time at which the predicted shock wave Mach number is almost sonic ( $M \approx 1.05$ ). The theory assumes no counter pressure ( $p_0 \ll p$ ). For this reason it would be expected that sonic shock speed would actually be reached at an earlier time and smaller radius than shown. However, this figure provides a conservative estimate of the possible extent of damaging shock phase pressure loadings and of the time scale involved in the shock phase phenomenon. These theoretical predictions for the time at which the shock is acoustic were 22 micro-seconds at 1.71 inches for the 1600 in-lb energy level, 36 micro-seconds at 2.31 inches for the 7493 in-lb energy and 44 micro-seconds at 5.4 inches for the 12323 in-lb energy level.

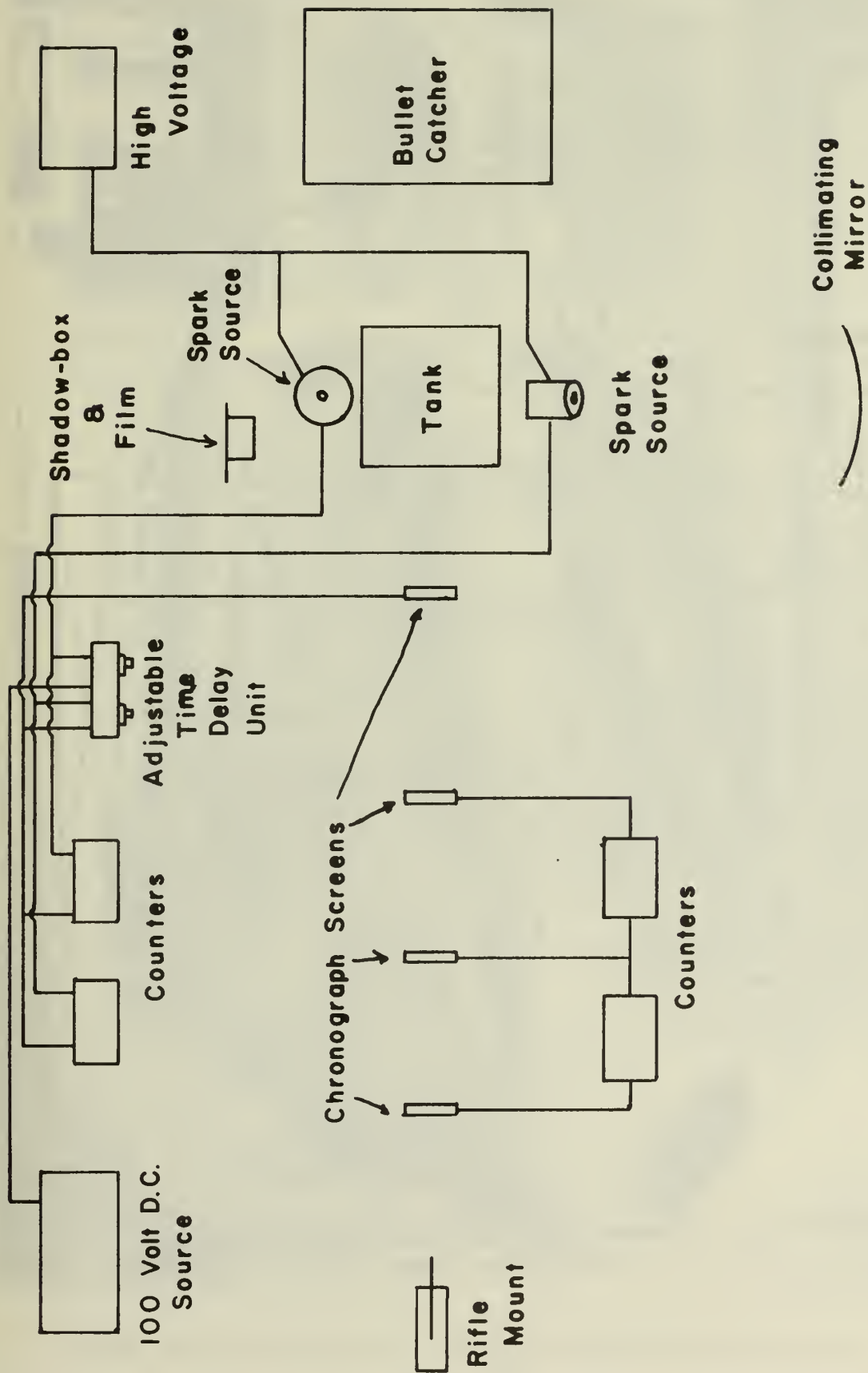


FIGURE III-1. Ballistic Range Components

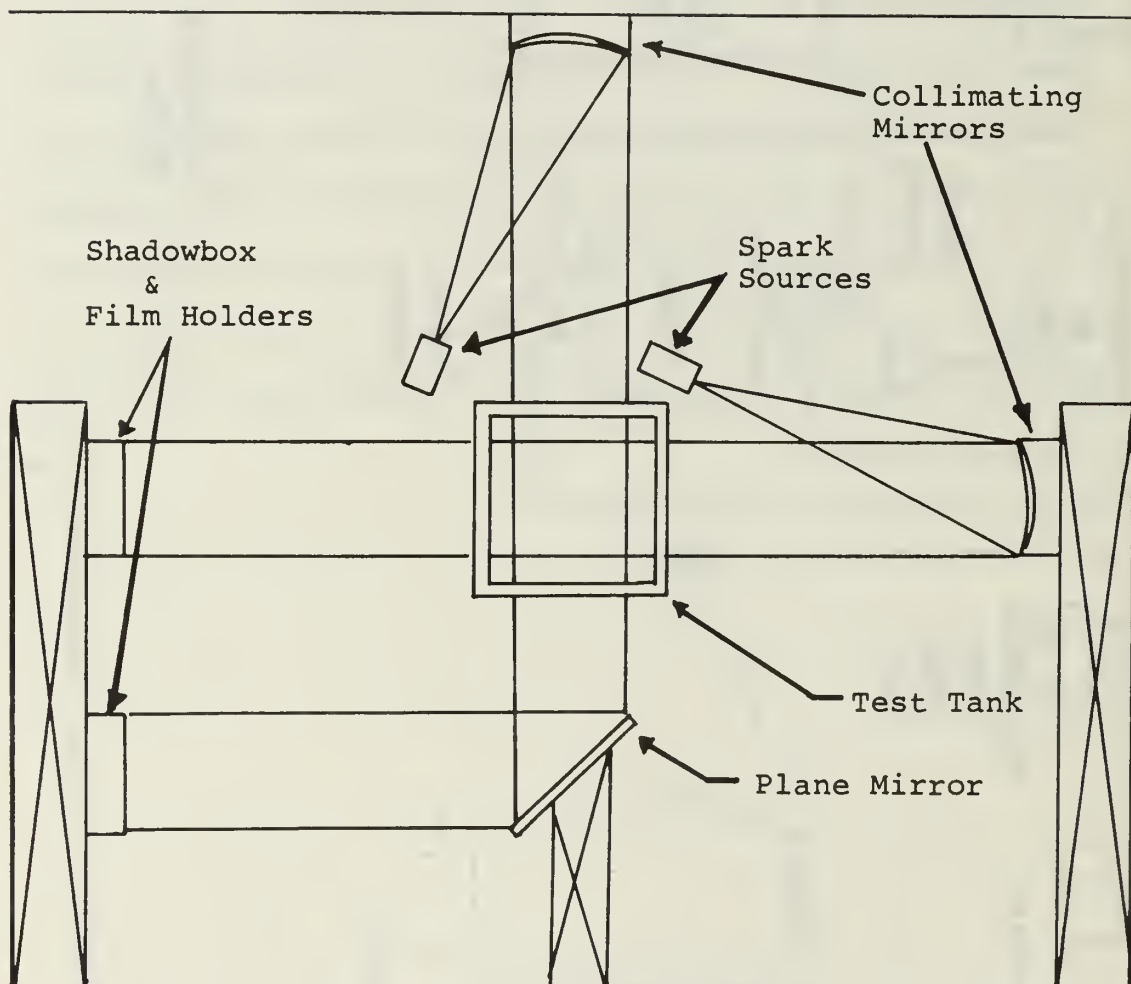


FIGURE III-2. Schematic of Shadowgraph Apparatus  
(Down-range View)

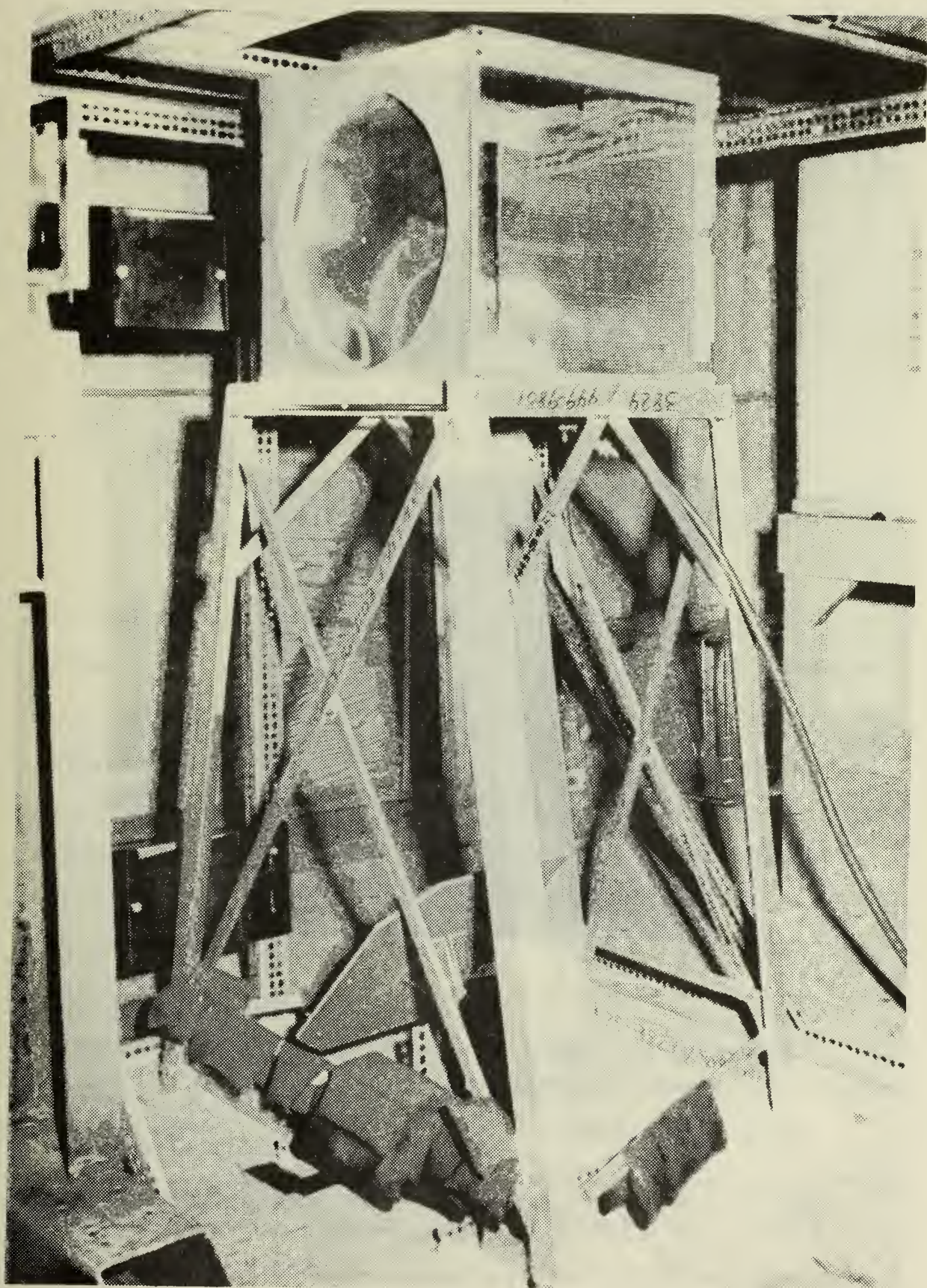


FIGURE III-3. Shadowbox, Tank and Stand Installation

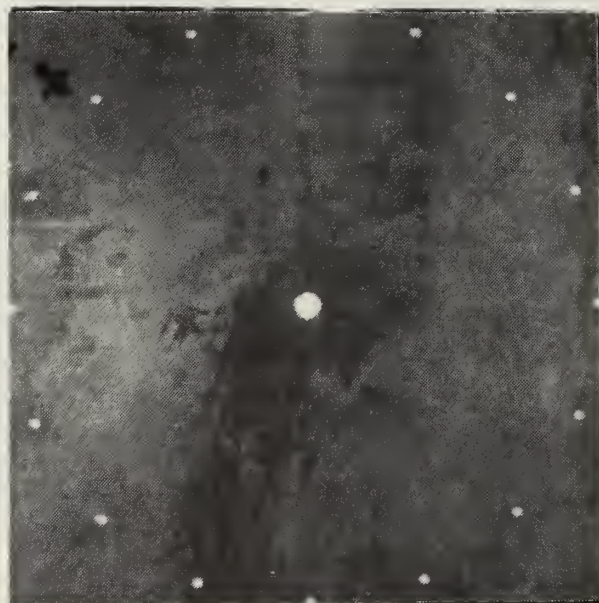


FIGURE III-4. Front Wall Test Specimen,  
Pre-punched Hole

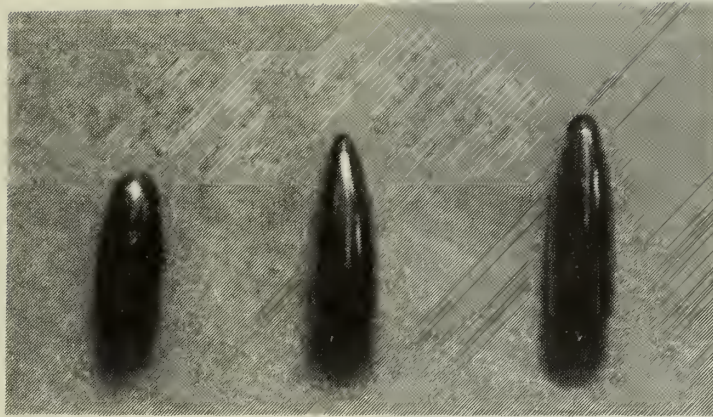
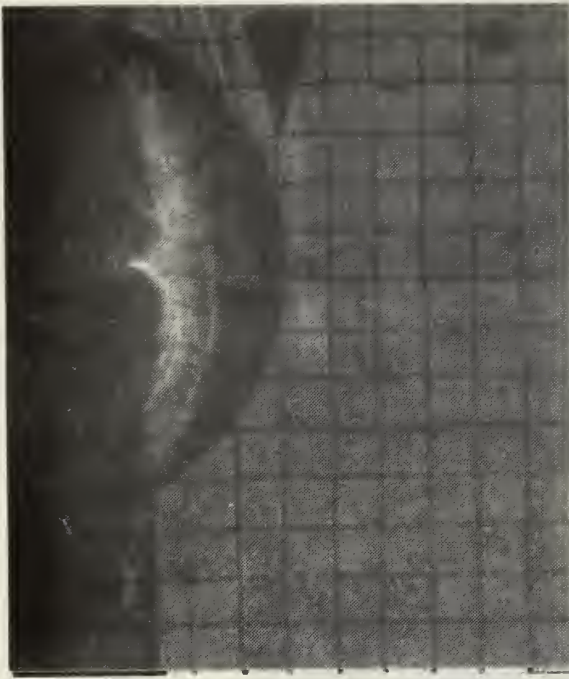


Figure III-5. Projectile Shapes (L. to R.: .22 caliber,  $m = 5.75 \times 10^{-3}$  lb, .222 caliber,  $m = 6.43 \times 10^{-3}$  lb, .222 caliber,  $m = 7.85 \times 10^{-3}$  lb)

| Caliber                                                                            | .22 Long Rifle        | .222 Remington        | .222 Remington        |
|------------------------------------------------------------------------------------|-----------------------|-----------------------|-----------------------|
| Impact Velocity, $V_0$<br>(ft/sec)                                                 | 1200                  | 2500                  | 2900                  |
| Projectile Mass, $m$<br>(lb <sub>m</sub> )                                         | $5.75 \times 10^{-3}$ | $6.43 \times 10^{-3}$ | $7.85 \times 10^{-3}$ |
| Impact Energy, $E_0$<br>(in-lb)                                                    | 1600                  | 7493                  | 12323                 |
| Experimental Drag<br>Coefficient, $C_D$                                            | 1.20                  | 0.45                  | 0.50                  |
| Frontal Area of<br>Projectile After<br>Traversing Fluid, $A$<br>(in <sup>2</sup> ) | 0.122                 | 0.098                 | 0.165                 |
| Equivalent Flat<br>Plate Area, $f (=C_D A)$<br>(in <sup>2</sup> )                  | 0.146                 | 0.044                 | 0.083                 |

Figure III-6. Projectile Parameters



$t = 1 \mu\text{sec}$



$t = 24 \mu\text{sec}$

Figure III-7. Shadowgraphs After Projectile Impact Through a Pre-punched Front Wall

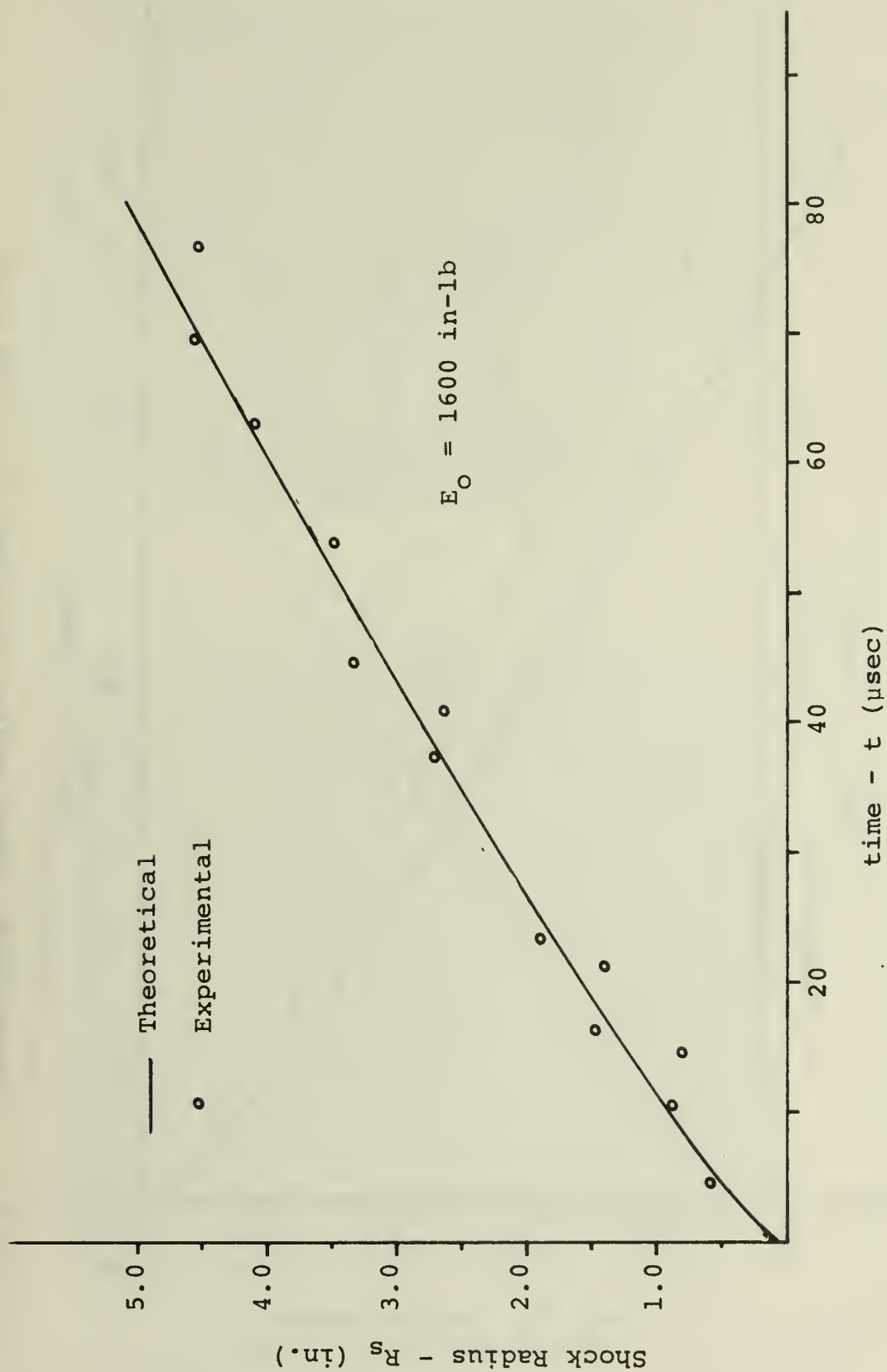


Figure III-8. Shock Radius vs. Time,  $E_0 = 1600 \text{ in-lb}$

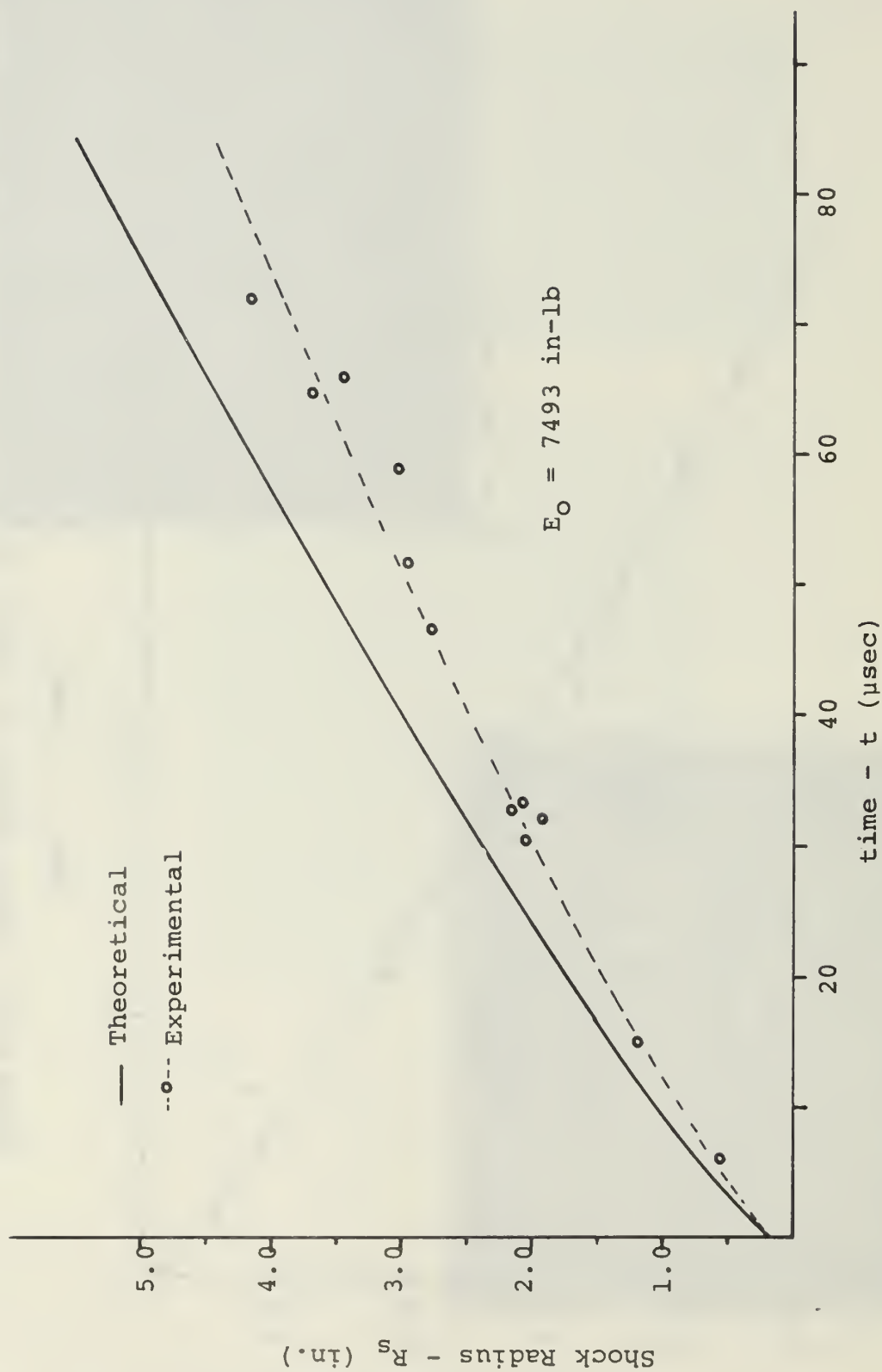


Figure III-9. Shock Radius vs. Time,  $E_0 = 7493 \text{ in-lb}$

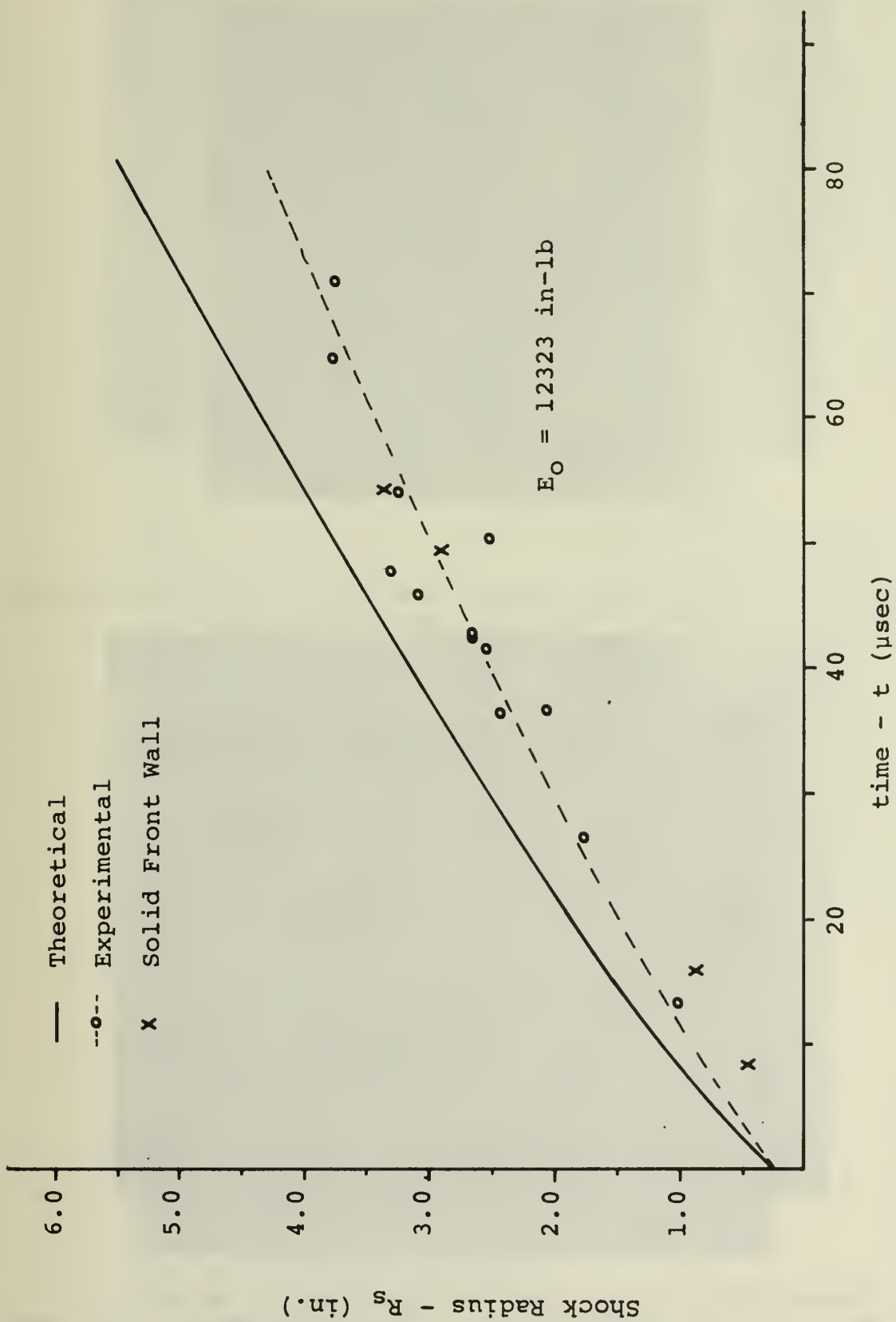


Figure III-10. Shock Radius vs. Time,  $E_0 = 12323 \text{ in-lb}$

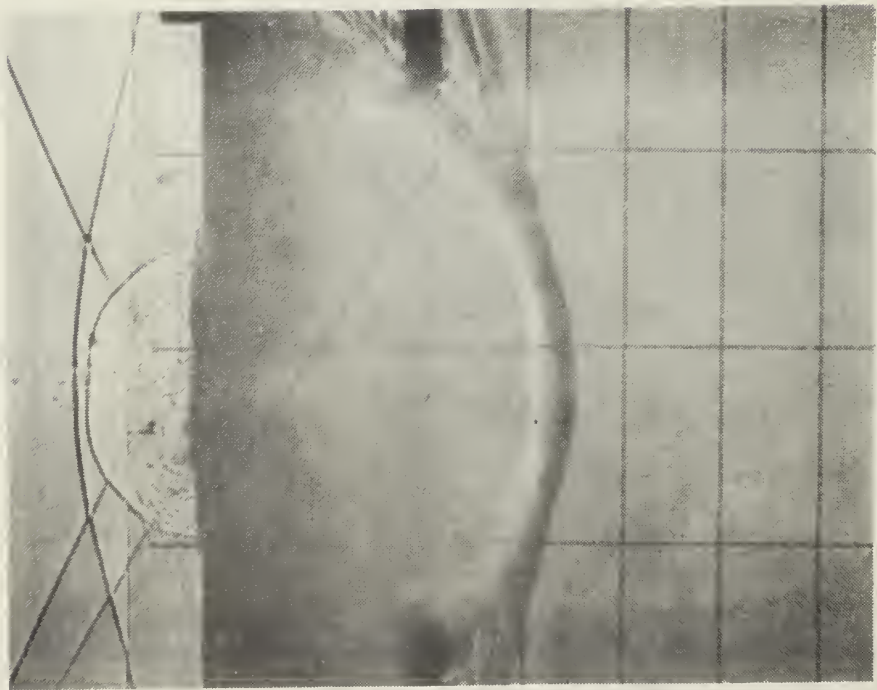


Figure III-11. Shock Waves Resulting from 0.22 Caliber  
Projectile Impact with a Solid Entry  
Wall

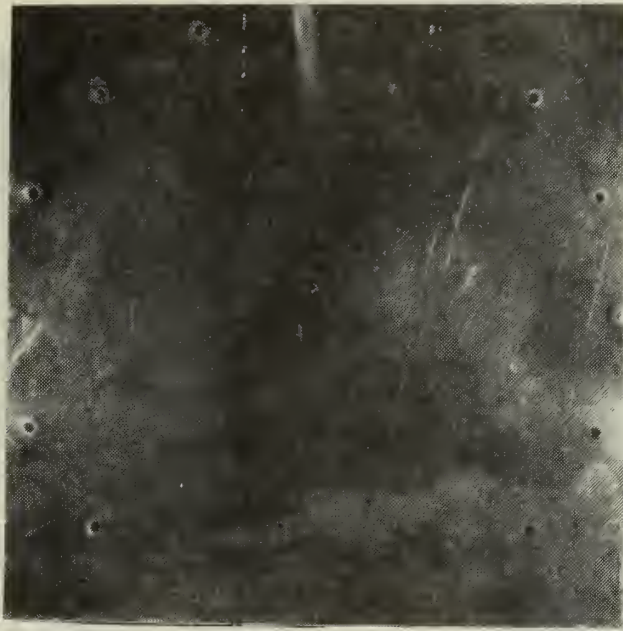


Figure III-12. Solid Front Wall After Test (6061-T6 Aluminum, .043 in. thick,  $E_0 = 12323$  in-lb)

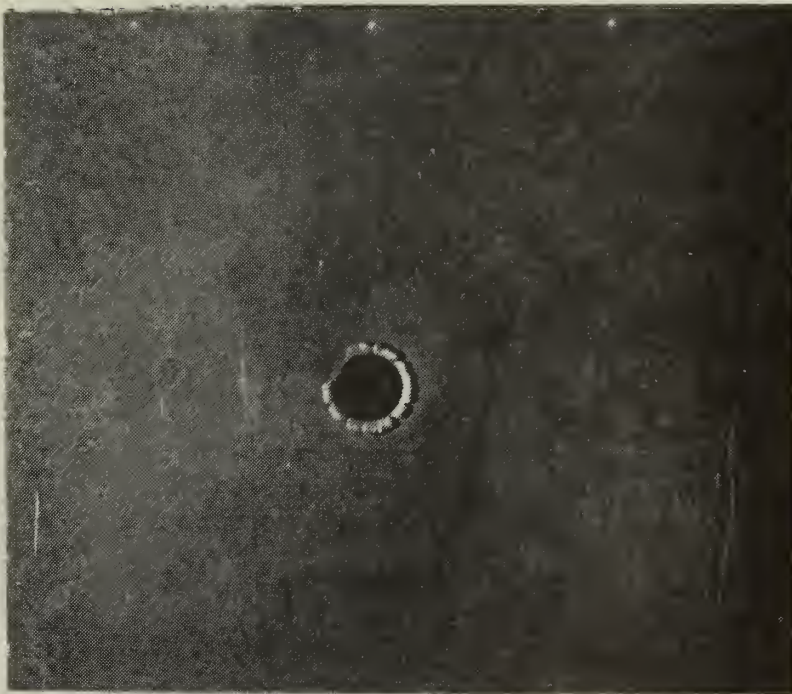


Figure III-13. Typical Damage to Solid Front Wall at Point of Impact (Front view, 6061-T6 Aluminum, .043 thick,  $E_0 = 12323$  in-lb)

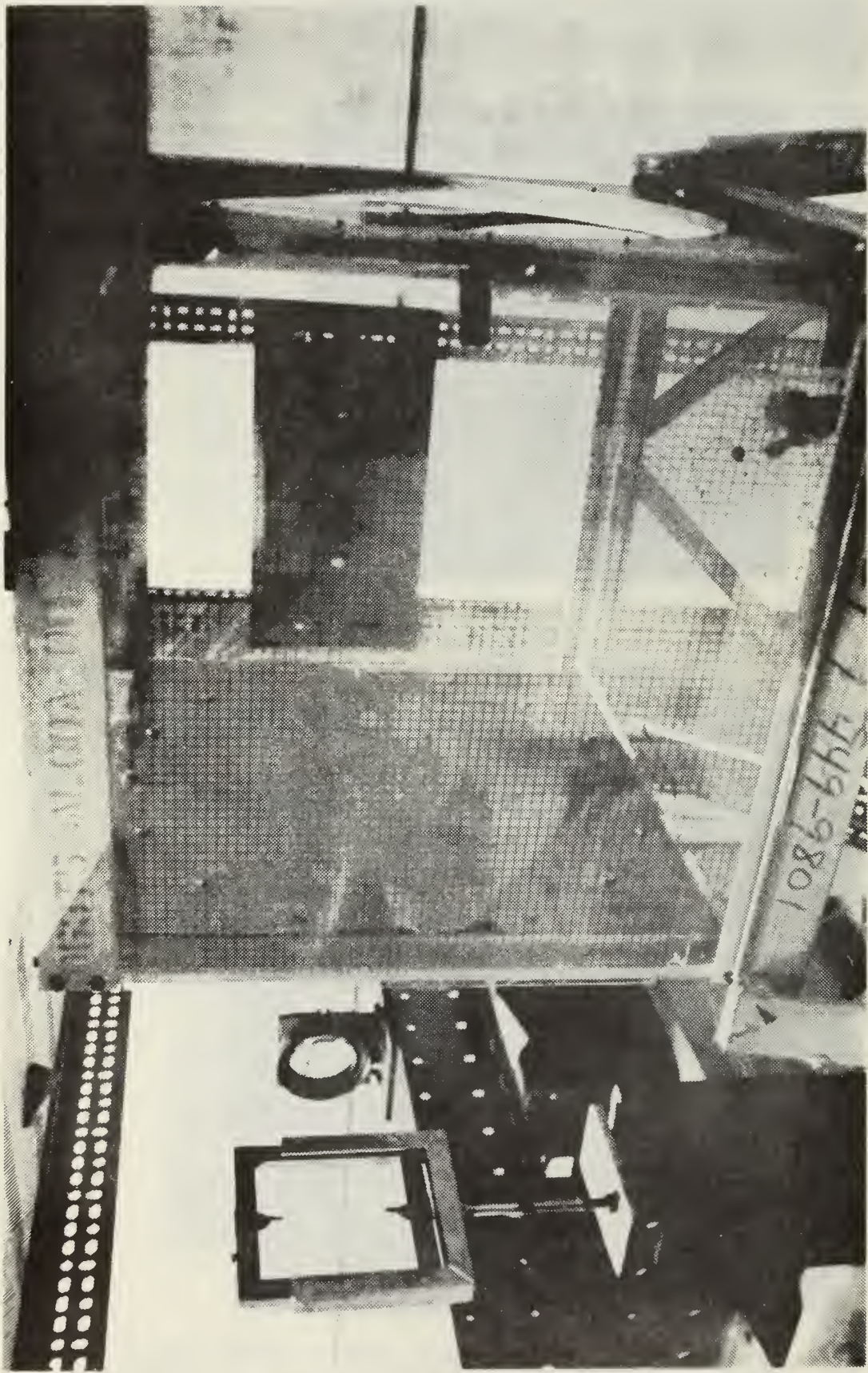


Figure III-14.. Damage to Solid Front Wall (Mounted on Tank)

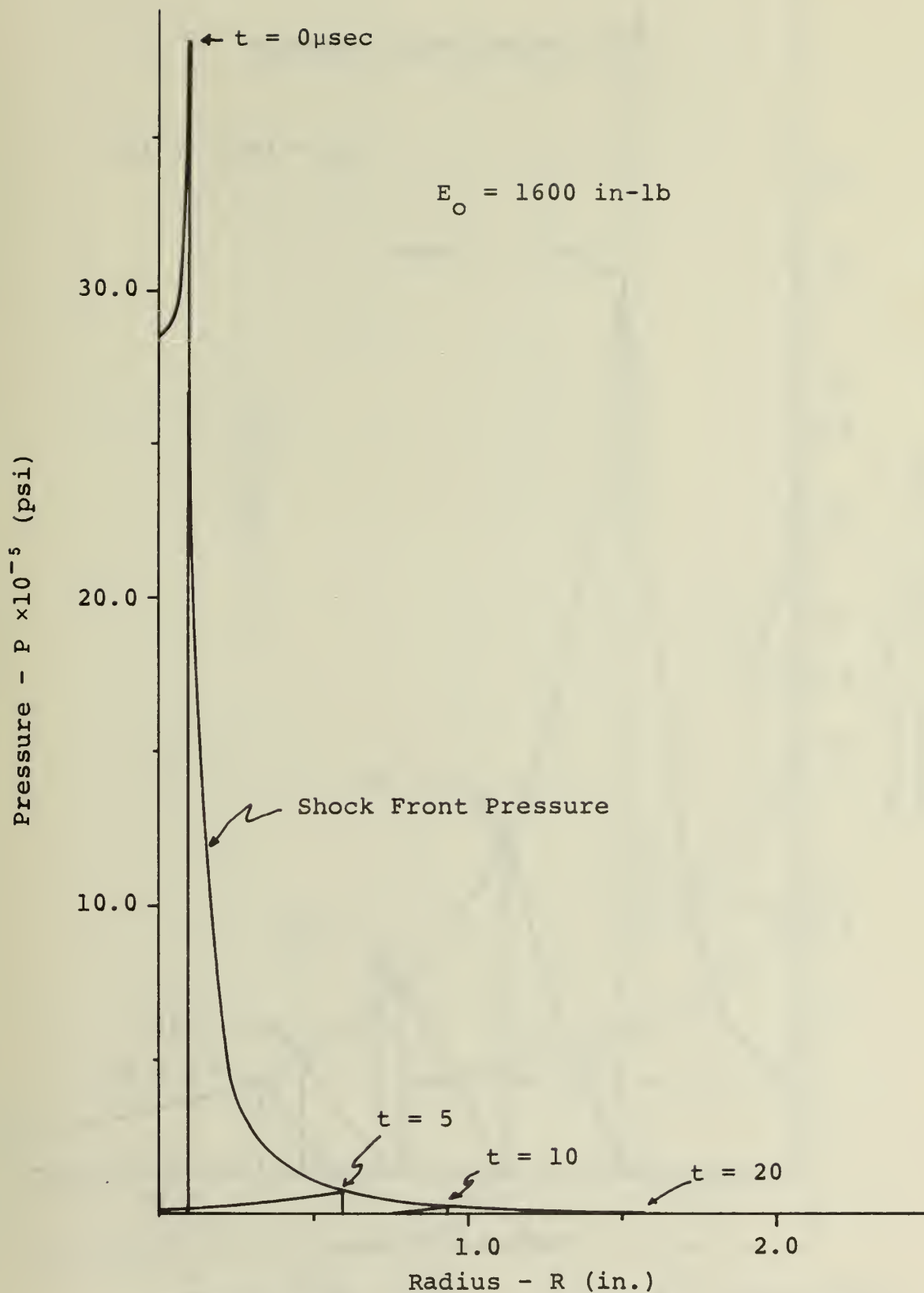


Figure III-15. Pressure vs. Radius from Impact - Complete Profile,  $E_0 = 1600$  in-lb

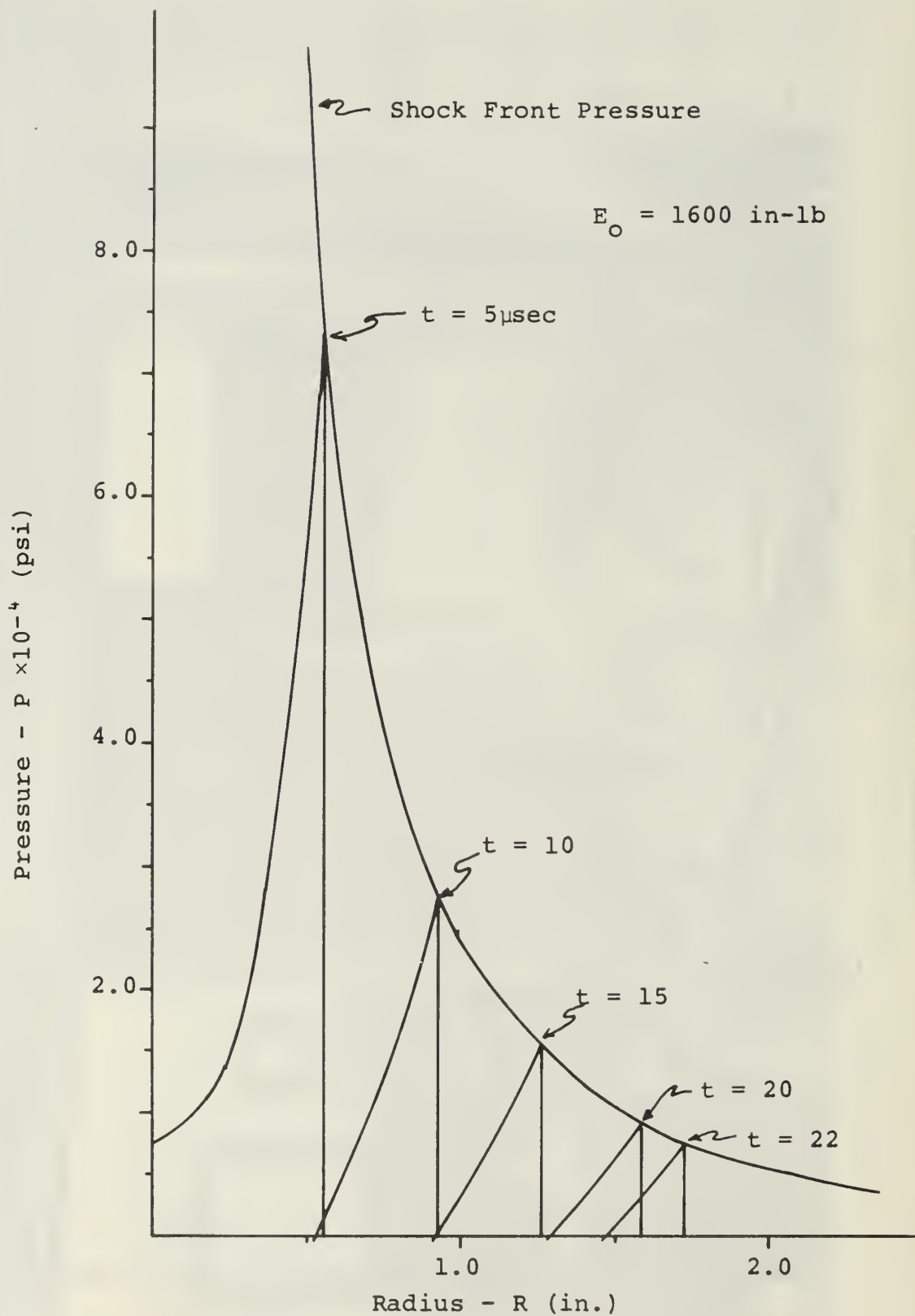


Figure III-16. Pressure vs. Radius from Impact,  
 $E_0 = 1600 \text{ in-lb}$

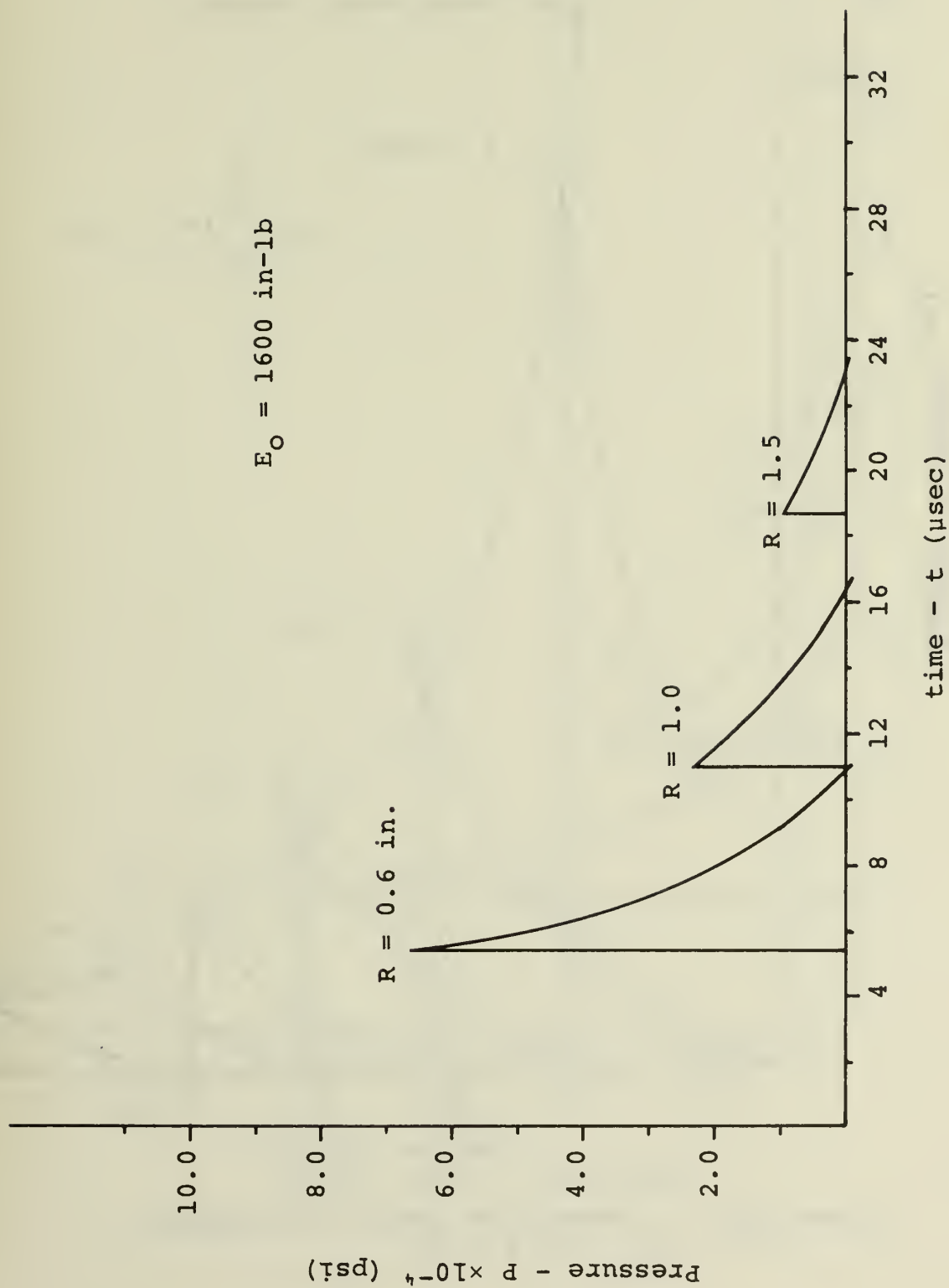


Figure III-17. Pressure vs. Time for Three Radii,  $E_0 = 1600 \text{ in-lb}$

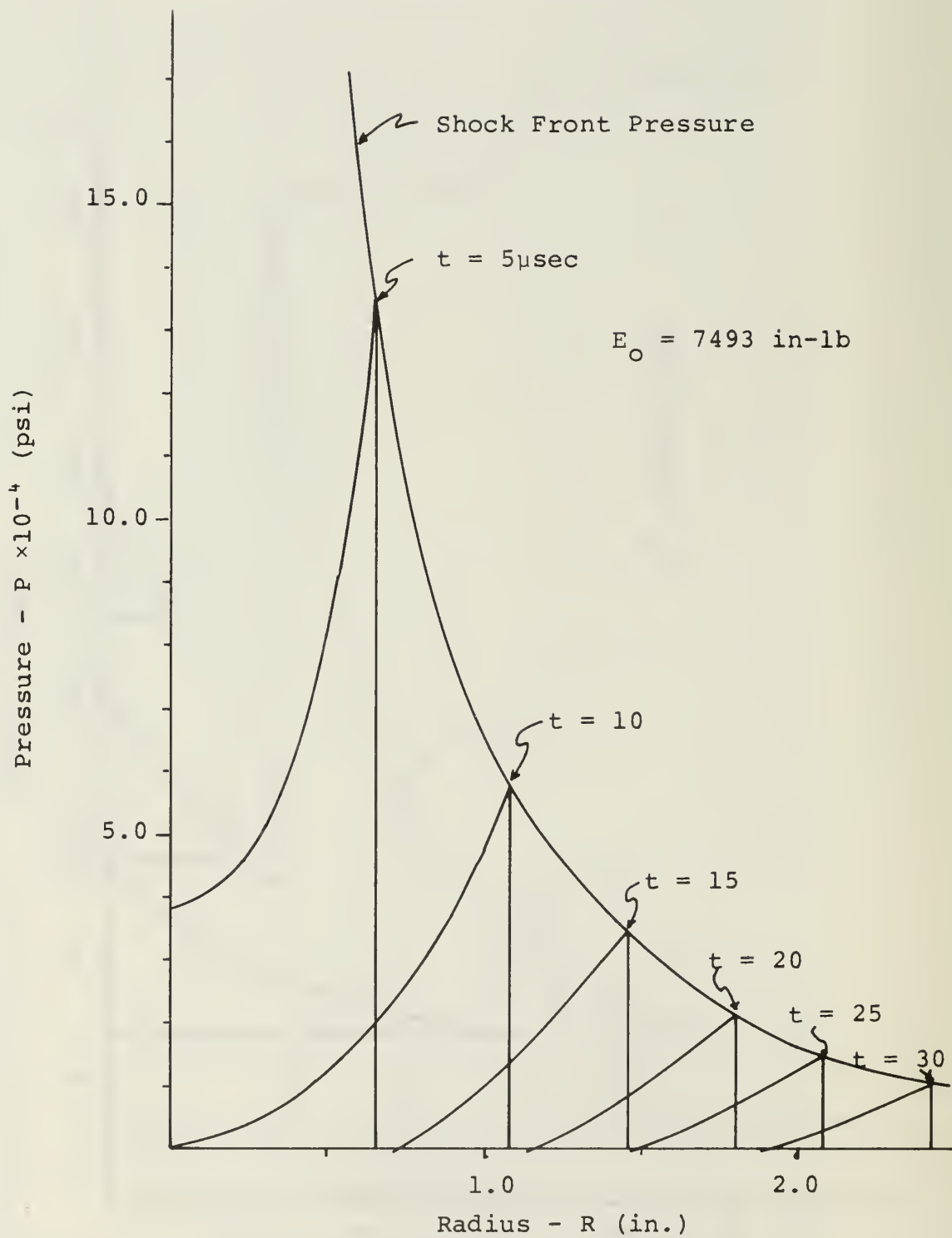


Figure III-18. Pressure vs. Radius from Impact,  
 $E_0 = 7493 \text{ in-lb}$

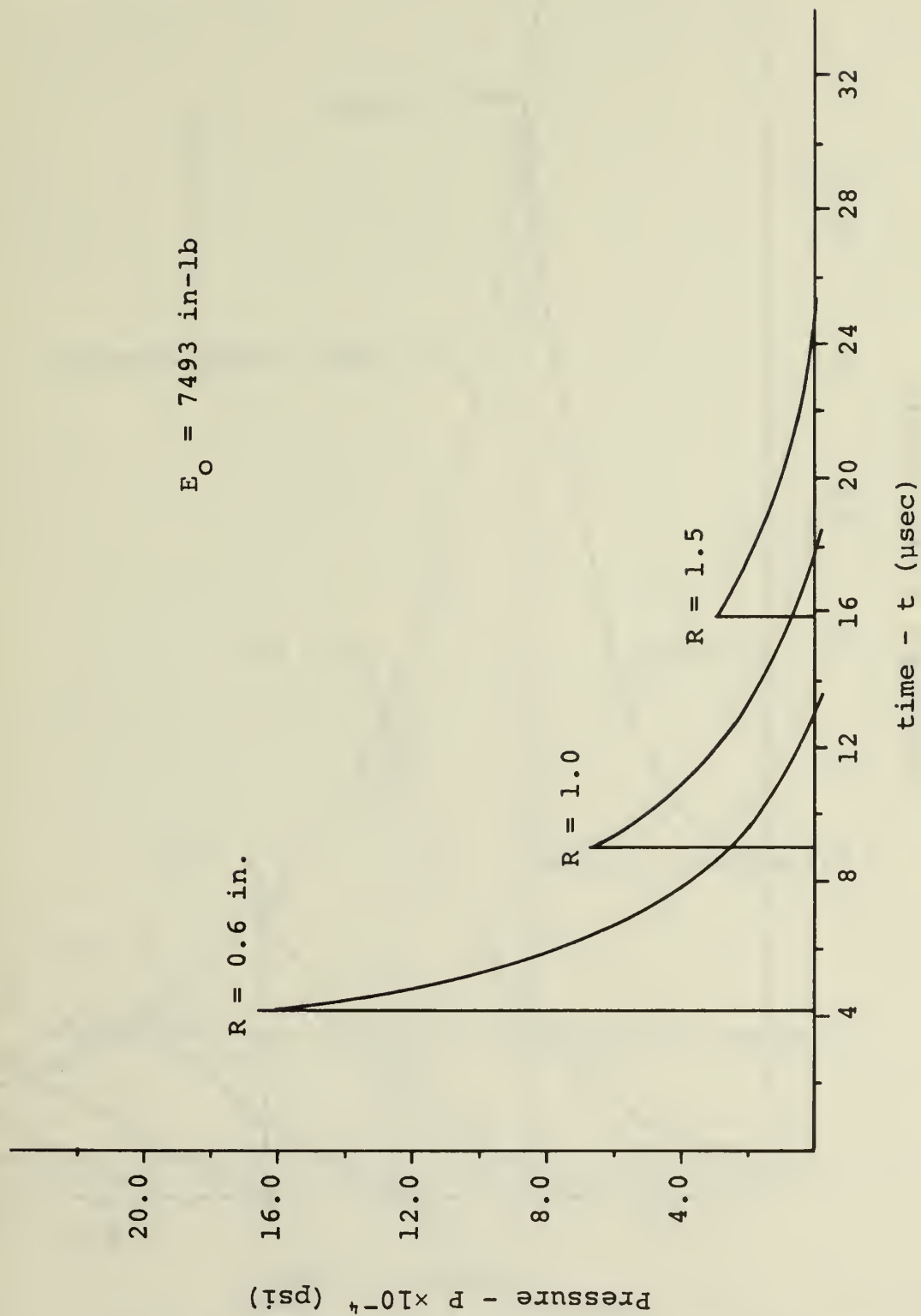


Figure III-19. Pressure vs. Time for Three Radii,  $E_0 = 7493 \text{ in-lb}$

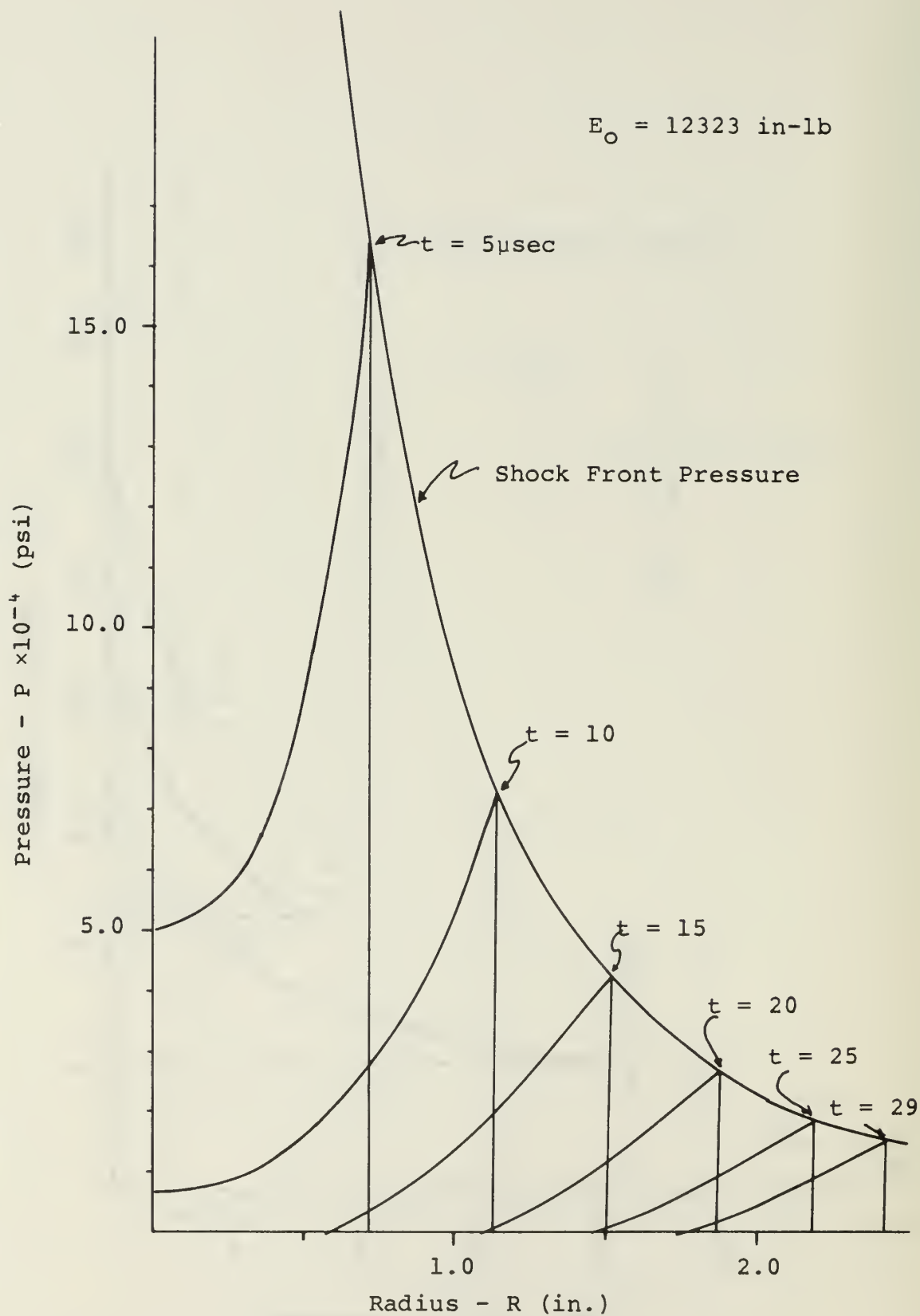


Figure III-20. Pressure vs. Radius from Impact,  
 $E_0 = 12323 \text{ in-lb}$

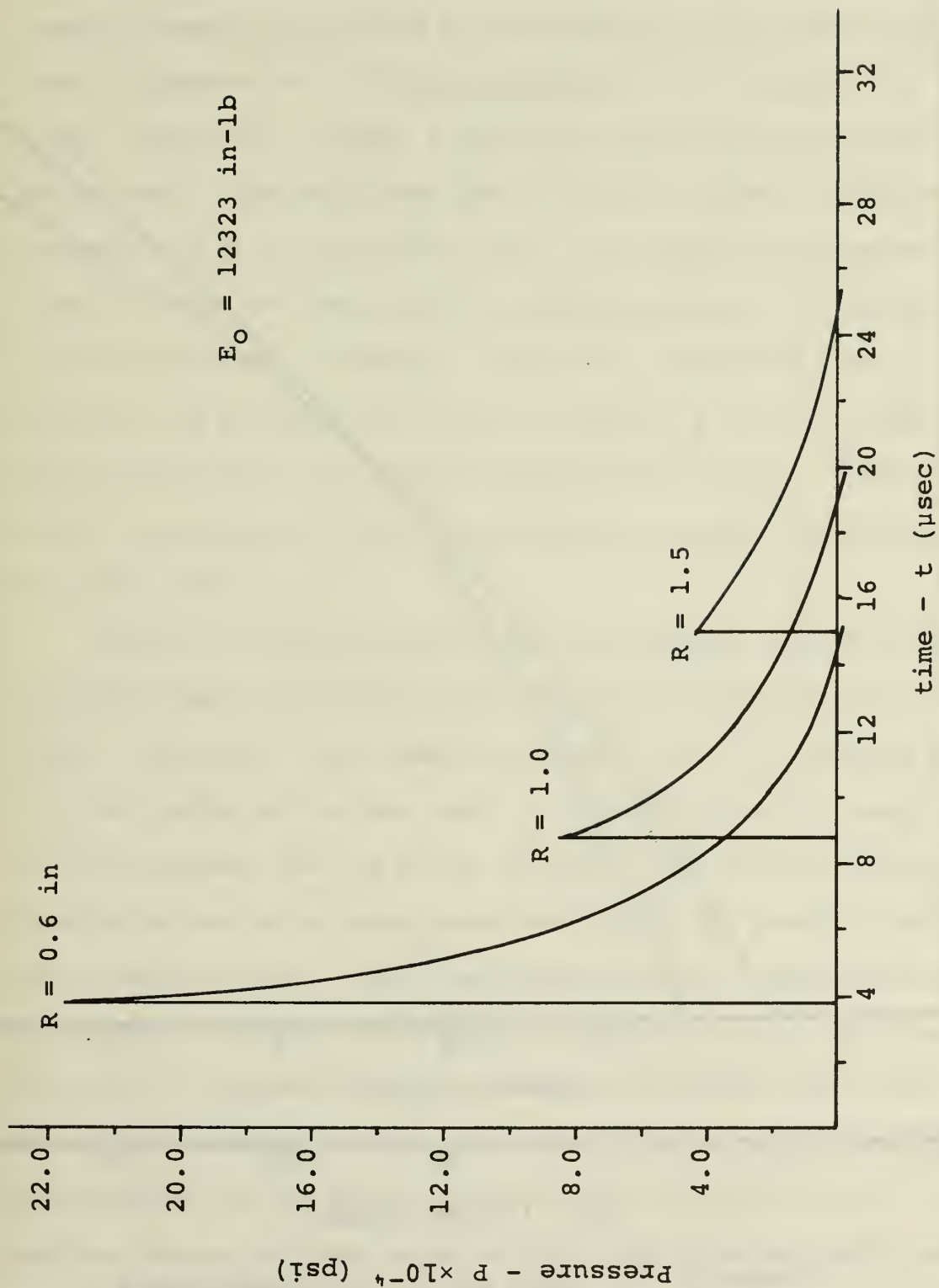


Figure III-21. Pressure vs. Time for Three Radii,  $E_O = 12323 \text{ in-lb}$

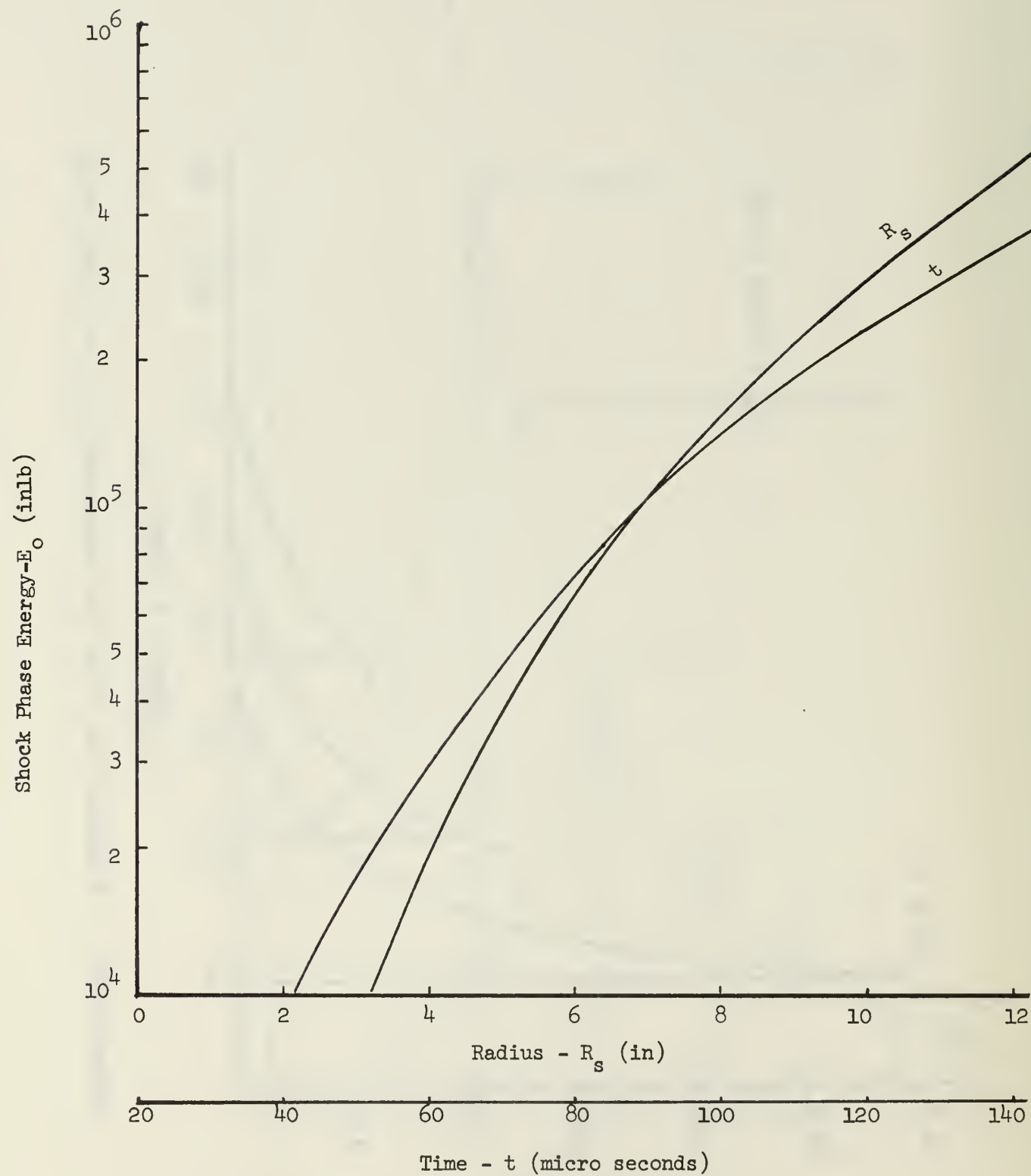


Figure III-22. Radius and Time for Acoustic Shock Speed in Water Verses Energy Input

#### IV. DRAG PHASE OF HYDRAULIC RAM

After protrusion from the entry wall the projectile transfers its remaining energy to the fluid by the production of the shock phase previously discussed and by viscous dissipation as it traverses the tank fluid. Figure IV-1 presents a qualitative view of this projectile energy decay. The shock phase does not, in most cases of interest, dissipate all of the projectile energy. The projectile subsequently travels through the tank until the remaining energy is dissipated or until the exit wall is reached. During this latter drag phase of hydraulic ram a cylindrical cavity is formed as a result of radial velocity imparted to the fluid by the projectile motion. Inside this cavity are trapped air which entered during the entry wall penetration and fluid vapors.

During the drag phase projectile spin and angle of attack combine to produce Magnus sideforces which perturb the projectile from a straight path. Furthermore, large stagnation pressures in the flow cause projectile deformation and in some cases the projectile does not remain intact. It is also likely that the energy imparted to the fluid by viscous dissipation during the shock phase would modify the pressure distribution behind the shock. Fuhs<sup>9</sup> has suggested that a characteristic time separating the drag and shock phases of hydraulic ram be identified as the point in time where projectile stagnation pressure just exceeds the shock front pressure. This characteristic time was approximately 30 micro-seconds for the 1600 in-lb energy level projectile tested. Interactions between the shock phase and drag phase pressure loadings would be largest for times close to this characteristic time.

These factors make an analytical estimation of drag phase pressure

loading exceedingly difficult. Stepka<sup>4</sup> has suggested that during the drag phase the projectile energy decay may be approximated by solutions of a simple equation of motion

$$D = -m \frac{dV}{dt} = C_D \frac{1}{2} \rho V^2 A \quad (\text{IV-1})$$

In general projectile deformation would require both drag coefficient and area variation with time. By assuming constant projectile area, drag coefficient, and mass equation IV-1 may be integrated to yield the projectile velocity decay as a function of distance traveled through the fluid

$$\frac{V}{V_0} = e^{-Bx} \quad (\text{IV-2})$$

where  $B = \rho C_D A / 2m$  and  $V_0$  is the initial velocity of the drag phase.

Projectile position as a function of time is given by

$$x = \frac{1}{2} \ln (BV_0^2 t + 1) \quad (\text{IV-3})$$

From this crude analysis an estimate of the rate of energy transfer to the fluid may be made from:

$$\frac{E}{E_0} = \frac{1}{[1 + BV_0^2 t]^2} \quad (\text{IV-4})$$

A series of experiments<sup>7</sup> were conducted to determine the drag phase energy dissipation. Using the experimental setup discussed in section III spark shadowgraphs of the drag phase were taken for three initial impact energy levels. Figure IV-2 shows typical results. The cylindrical cavity formation is clearly shown in these shadowgraphs. The tip

of the illuminated cusp marks the position of the projectile nose. From measurements of projectile position versus time the energy decay of the drag phase may be determined. Figure IV-3 through IV-5 show a comparison of the experimental and theoretical positions for the three energy levels tested. It was hoped that this data would yield an estimate of the energy loss during the shock phase, hence the unknown initial drag phase velocity  $V_0$  defined in Figure IV-1. Data scatter, however, was too great to make such an estimate and  $V_0$  was subsequently assumed to be equal to the impact velocity. Data scatter was attributed to variations, from shot to shot, in projectile path and deformation. It was concluded that trajectory parameters hence drag phase energy decay is very sensitive to projectile attitude and deformation during fluid traverse.

Approximately 51% of the 22 caliber projectile impact velocity was lost within 1.5 inches of the front wall and within 135 micro-seconds. The 22.2 caliber projectile with an initial energy of 7493 in-lb lost only 17% of its impact velocity at 1.5 inches while those with an energy of 12,323 in-lb lost 25%. The differences in these results are attributed to differences in projectile deformation rates. The lead 22 caliber blunt projectile deforms more rapidly than the copper jacketed 22.2 caliber rounds. It would be expected that this round would lose a larger percentage of the initial energy at a constant penetration depth because of the resulting larger equivalent flat plate area ( $f = C_D A$ ). The percentage energy lost at a constant radius was also a function of the initial energy level for projectiles of the same construction. Increased initial energy produces larger viscous dissipation rates and larger deformation rates because of higher stagnation pressure loadings.

This effect is shown clearly by examining typical projectile shapes after fluid traverse as shown in Figure IV-6. The projectiles studied are known to be dynamically stable when the longitudinal axis is perpendicular to the flight path and hence they do not tumble. Stagnation pressures generated by the drag phase flow are large enough to cause large plastic deformations of these lead and copper jacketed projectiles. Since drag coefficient and area are changing during the drag phase it is more convenient to use an equivalent flat plate area to match experimental data to the predictions of equation IV-4. These results indicate that the exponential velocity decay can be used for a reasonable estimate of the drag phase energy loss if an equivalent flat plate area of the round in question can be determined experimentally. These data also indicate that the drag phase energy dissipation rate is very sensitive to the material and aerodynamic properties of the threat.

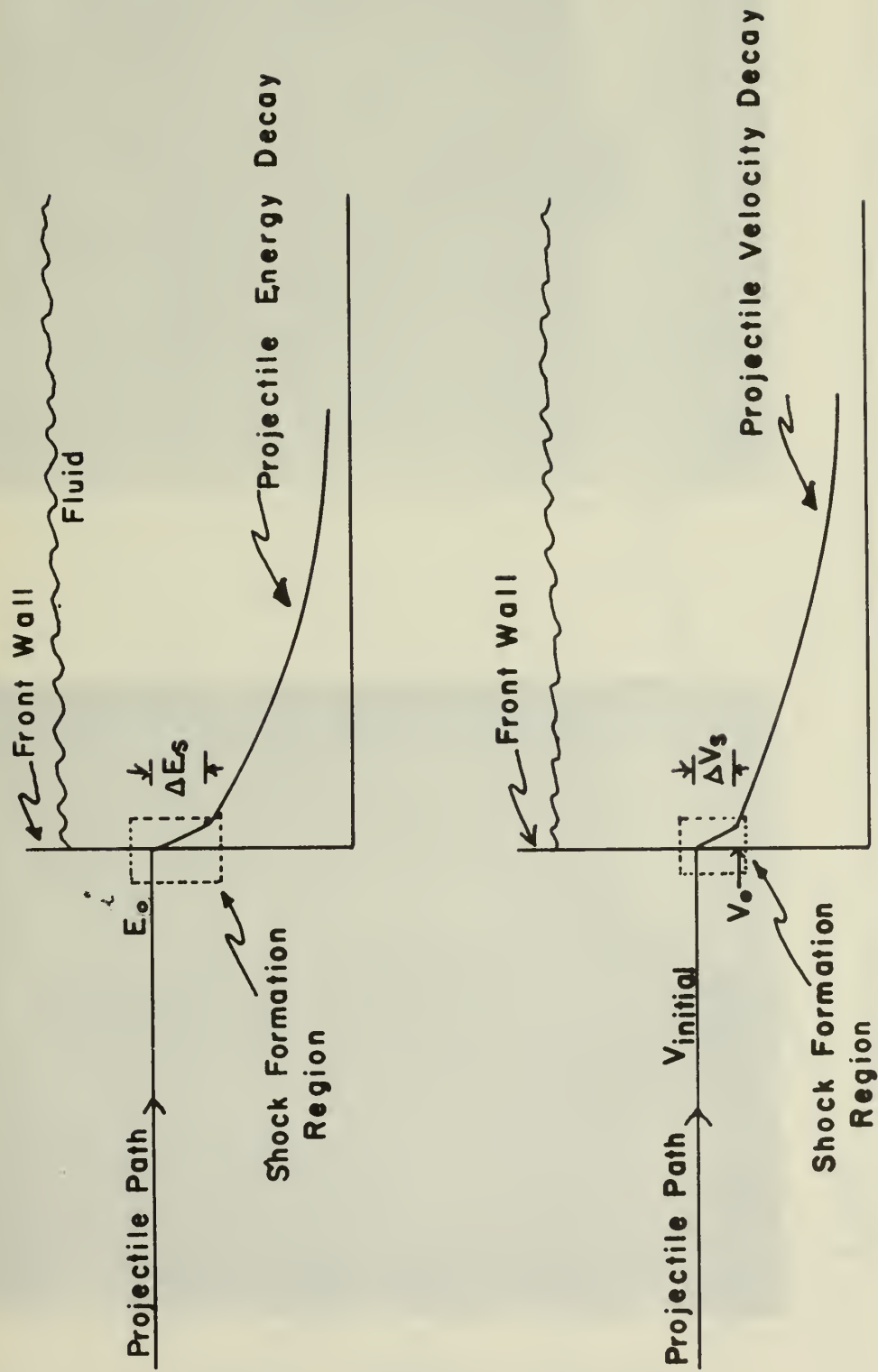


Figure IV-1. Qualitative View of Projectile Energy and Velocity Decay in the Fluid

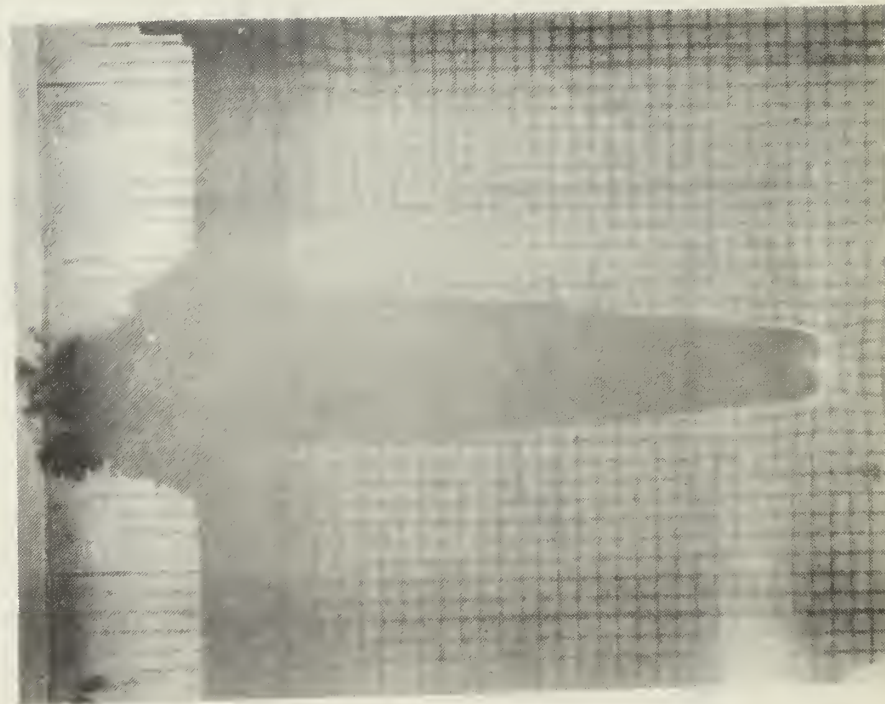
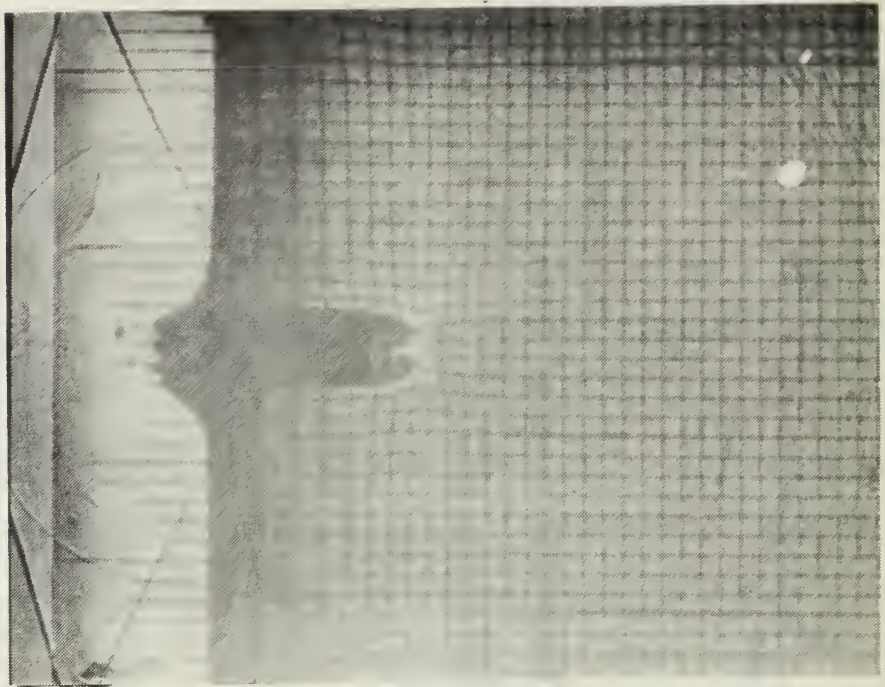


Figure IV-2. Cavity Growth Resulting from a  
Prepunched Hole Impact

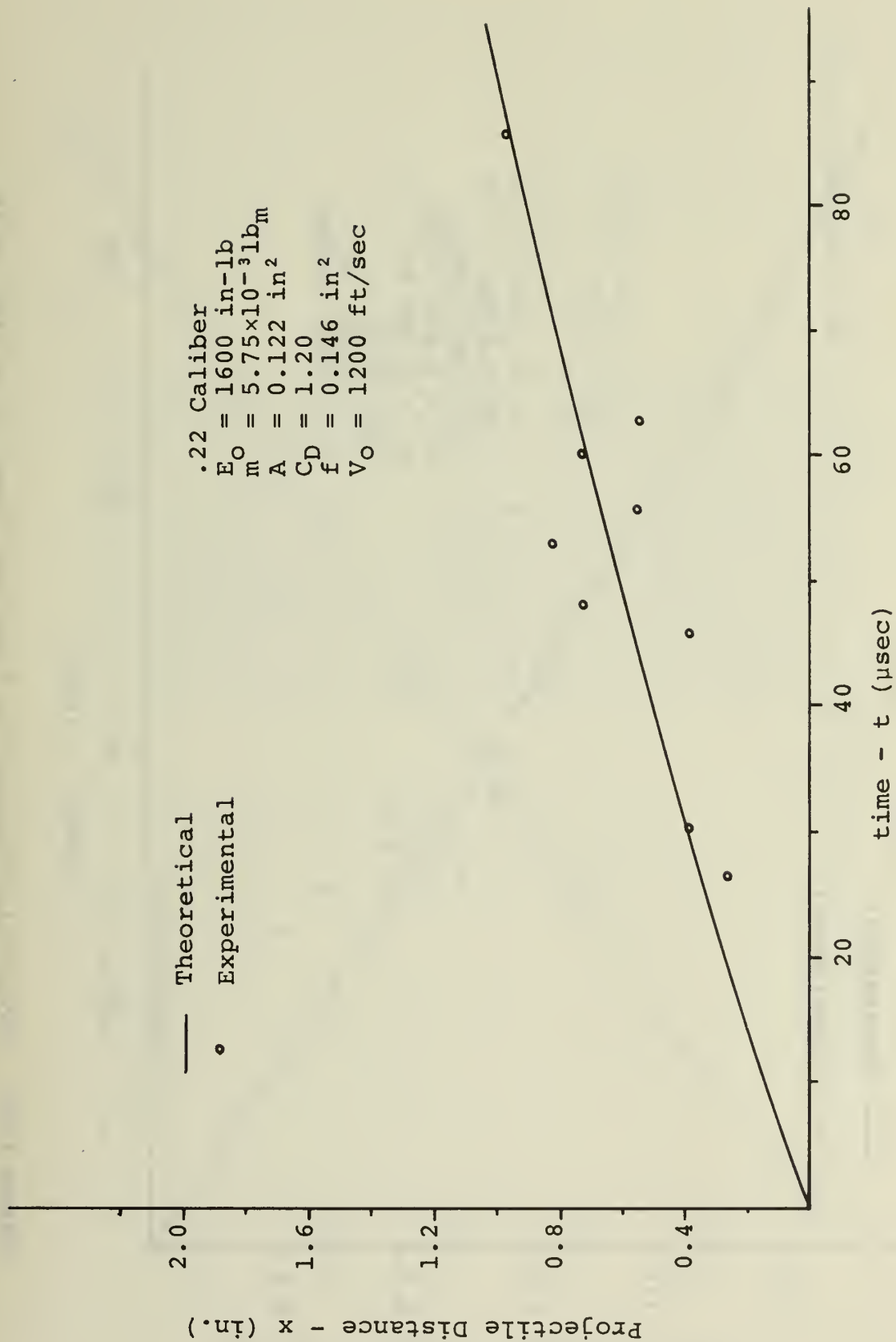


Figure IV-3. Projectile Distance Traveled in Fluid vs. Time,  $E_0 = 1600 \text{ in-lb}$

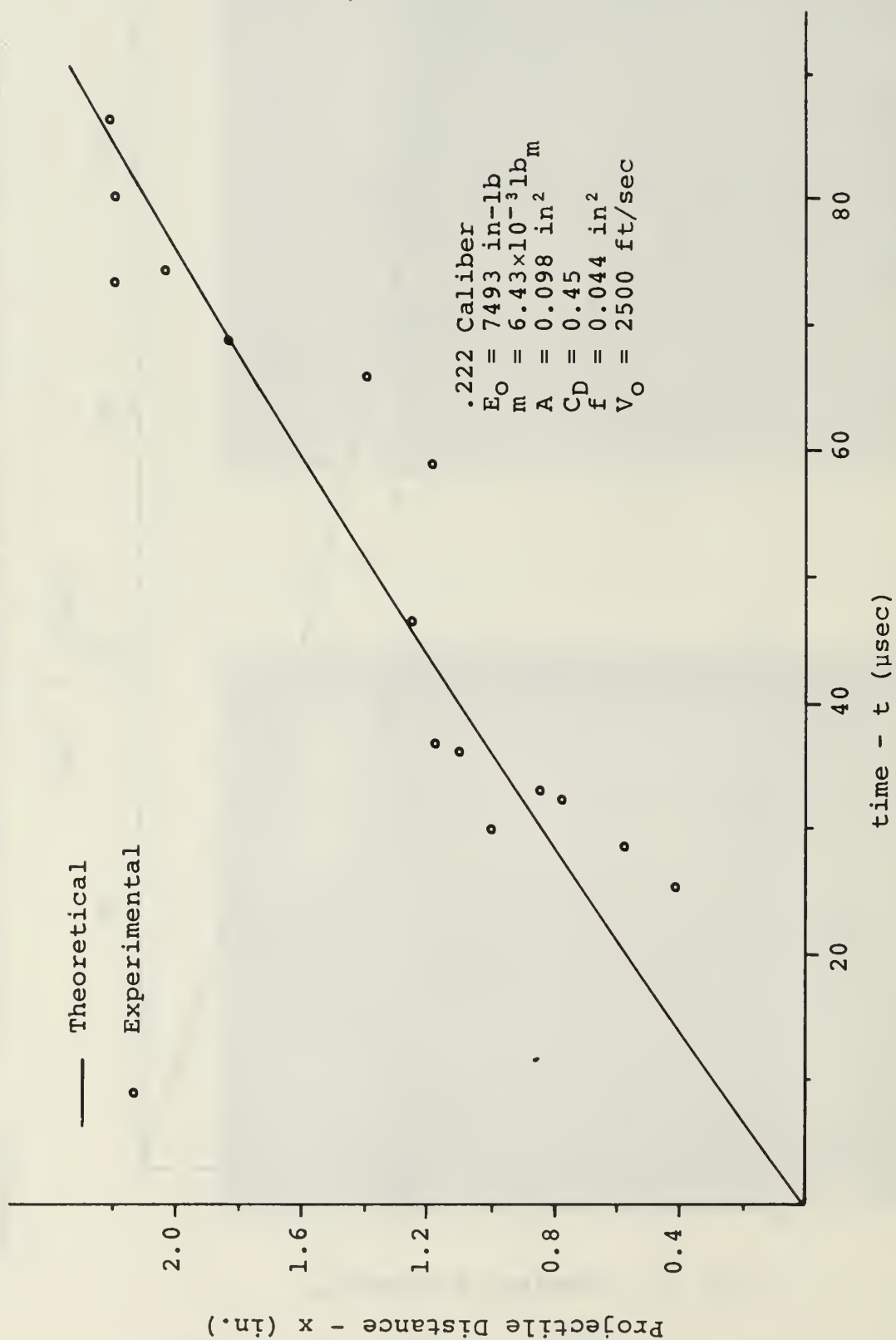


Figure IV-4. Projectile Distance in Fluid vs. Time,  $E_0 = 7493 \text{ in-lb}$

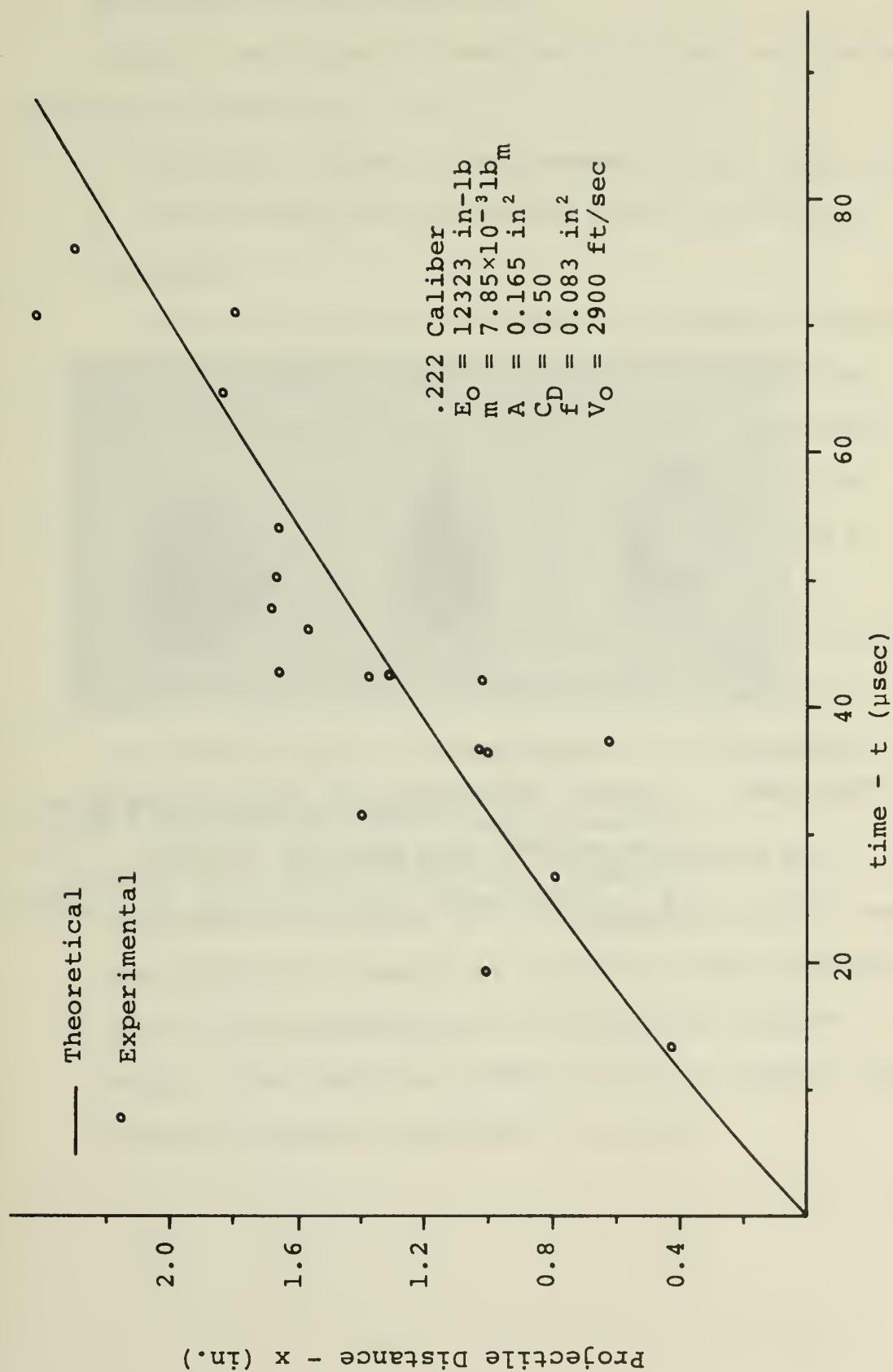


Figure IV-5. Projectile Distance in Fluid vs. Time,  $E_0 = 12323 \text{ in-lb}$



Figure IV-6. Typical Deformation of Projectiles After Coming to Rest in the Fluid Filled Tank - Pre-punched Hole Results (L. to R.: .22 caliber,  $E_o = 1600$  in-lb; .222 caliber,  $E_o = 7493$  in-lb; .222 caliber,  $E_o = 12323$  in-lb)

## V. Recommendations for Further Study

Hydraulic ram studies will continue in FY75 and the following list outlines the future work:

1. Information similar to that presented in this report will be collected using the higher energy levels of 30-caliber projectiles.
2. The test cell will be instrumented with pressure transducers to determine experimental pressure profiles during the shock phase of hydraulic ram for cells with rigid walls. A comparison of these results with predictions will allow an assessment of the Yurkovitch model and could provide a method for determining the shock phase energy loss  $E_0$ .
3. Fuel cell pressure loadings will be determined for cells with thin entry walls. A comparison with the results in item 2 should result in a determination of the fluid-wall motion interaction problem.
4. The test cell entry walls will be instrumented with strain gages to determine wall stresses during hydraulic ram. These data will be compared to theoretical predictions based upon both the experimental and the theoretical pressure loadings. The theoretical predictions will be obtained from the digital computer code SATANS<sup>10</sup> and BR-1HR.

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# VIII. APPENDIX

## COMPUTER PROGRAM

```

*****
*
* THIS PROGRAM CALCULATES THE FOLLOWING
* PART I
* 1. SHOCK RADIUS VERSES TIME
* 2. SHOCK MACH NUMBER VERSES TIME
* PART II
* 1. PRESSURE VERSE TIME AND RADIUS
* FROM IMPACT BEHIND THE SHOCK
* FOR A GIVEN FLUID AND IMPACT ENERGY,EO. THIS PROGRAM
* ASSUMES: SHOCK RADIUS IS PROPORTIONAL TO TIME TO THE
* C.8 POWER UNTIL ACCUSTIC, A POWER LAW DENSITY PROFILE
* BEHIND THE SHOCK, A STRONG SHOCK, ADIABATIC ACROSS
* THE SHOCK, THE UNDISTURBED FLUID PRESSURE IS ESSEN-
* TIALY ZERO, SPECIFIC INTERNAL ENERGY IN UNDISTURBED
* FLUID IS ESSENTIALLY ZERO.
*
*****

```

### SYMBOL DESIGNATION

```

EO= IMPACT ENERGY OF PROJECTILE (IN-LB)
CO= SPEED OF SCUND FOR FLUID (FPS)
RHOO= DENSITY IN UNDISTURBED FLUID (LB/FT3)
DC= INCREMENT OF NON-DIMENSIONAL RADILS, DELTA
    ZHETA
DELT= INCREMENT OF TIME (MICRO-SEC)
ET= ENERGY/VOL. = 2*EO/(R**3)
F1= NON-DIMENSIONAL PRESSURE AT THE SHOCK VS.
    SHOCK MACH NO.
DODM= DERIVATIVE OF NON-DIMENSIONAL PARTICLE
    VELOCITY W.R.T. SHOCK MACH NO. VS SHOCK
    MACH NO.
VS= SHOCK MACH NC.
X= PERCENT EO LOST AT ENTRY WALL

```

```

DIMENSION ET(20),PSI1(20),F1(20),VS(20),DCDM(20)
1,RXMS(20),DRS(20),ARMS(20),DT(20),T(20),RE(20),
1RV(20),RDCD(20),XMS(20),RS(20),RPSI(20),RF(20)
DIMENSION TT(300),XM(300),R(300),F2(300),PSI2(300),
1DCDM2(300),Q(300),C(100),F(2,20),P(2,20)
DIMENSION CONRS(300),SHOCV(300),TCFOR(300)
DIMENSION FOR(20)
CC 500 J=1,20
FOR(J)=0.0
500 CCNTINUE
N=18
READ (5,100) EO,CO,RHOO,X,DC,DELT
READ (5,101)(ET(I),I=1,N)
READ (5,101)(PSI1(I),I=1,N)
READ (5,101)(F1(I),I=1,N)
READ (5,101)(VS(I),I=1,N)
READ (5,101)(DODM(I),I=1,N)
WRITE (6,200) EO,CO,RHOO,X,DC,DELT
DC 15 I=1,N
15 WRITE (6,201) ET(I),PSI1(I),F1(I),VS(I),DCDM(I)
PART I

```

```

C      PERCENTAGE OF INITIAL ENERGY DEPOSITED AND INITIAL
C      SHOCK RADIUS
C
C      EO=X*EO
C      RC=(EO*32.2*144./ (RHOO*CO*CO*2.*3.1416))**0.33333
C
C      INITIAL VALUE OF ENERGY/VOL.
C
C      ETO=2.*EO/(RO**3.0)
C
C      INVERT INPUT ARRAYS FOR USE WITH INTERPOLATION
C      ROUTINE, PIF2
C
C      DC 12 I=1,N
C      J=N-I+1
C      RE(I)=ET(J)
C      RPSI(I)=PSI1(J)
C      RF(I)=F1(J)
C      RV(I)=VS(J)
12  RDCD(I)=DGDM(J)
C
C      INTERPOLATE FOR INITIAL VALUES AT SHOCK
C
C      VSO=PIF2(ETO,RE,N,RV)
C      F10=PIF2(VSO,RV,N,RF)
C      PSI10=PIF2(VSO,RV,N,RPSI)
C      DCDM0=PIF2(VSO,RV,N,RDCD)
C
C      COMPUTE INITIAL TIME FOR DISTANCE RO
C
C      TC=RO/(CO*VSO*12.0)
C
C      ASSIGN SUBSEQUENT VALUES OF SHOCK MACH NO. AT WHICH
C      SHOCK RADIUS WILL BE COMPUTED
C
C      DC 10 I=1,N
C      IF (VSO-VS(I)) 1,2,2
1  GC TO 10
2  M=N-I+1
C      XMS(1)=VSO
C      GC TO 11
10 CONTINUE
C
C      COMPUTE SUBSEQUENT VALUES OF SHOCK RADIUS
C
11 RS(1)=RO
C      DO 20 J=2,M
C      XMS(J)=VS(J)
C      RS(J)=(2.*EO / (ET(I)) )**0.3333
C      I=I+1
20 CONTINUE
C      K=M-1
C
C      COMPUTE DELTA TIME CORRESPONDING TO SHOCK MACH NO.
C      AND SHOCK RADIUS
C
C      DC 30 I=1,K
C      DRS(I)= RS(I+1)-RS(I)
C      ARMS(I)=2./ (XMS(I)+XMS(I+1))
30 DT(I)=DRS(I)*ARMS(I)/(CO*12.0)
C      T(1)=TC
C      DC 40 J=2,M
40 T(J)= T(J-1)+DT(J-1)
C      WRITE (6,102)
C      WRITE (6,103) EO
C      WRITE (6,110)
C
C      PRINT SHOCK MACH NO. AND SHOCK RADIUS VS TIME
C
C      DC 50 I=1,M
50 WRITE (6,111) T(I),XMS(I),RS(I)
100 FORMAT (6E10.0)

```

```

1C1 FORMAT (8E10.0)
102 FCRMAT (1H,/,39X, 'ENERGY',15X, 'FLUID' )
103 FCRMAT (29X,1E20.7)
110 FCRMAT (1H,/,39X 'TIME',17X,'MACH',17X,'RADIUS' )
111 FCRMAT (29X,3E20.7)
200 FCRMAT (/, 6E20.7)
2C1 FORMAT (15X,5E20.7)

```

C  
C  
C  
C  
C  
C

## PART II

INITIALIZE VARIABLES AND ASSIGN VALUES USED WITH  
NCN-DIMENSIONAL PRESSURE DISTRIBUTION FUNCTION

```

BBB=T(M)*1.E06+1.05
L=BBB
TT(1)=0.0
XM(1)=XMS(1)
R(1)=R0
F2(1)=F10
PSI2(1)=PSI10
DCDM2(1)=DCDM0
Q(1)=3.*(PSI10-1.0)
B=-0.25
I=1.0/DC +1.05
C(1)=0.0
WRITE (6,301)
WRITE (6,302) TT(1),XM(1),R(1)
WRITE (6,303)
DC 60 J=2,N
6C C(J)=C(J-1)+DC

```

C  
C  
C  
C

CCMPUTE NON-DIMENSIONAL AND DIMENSIONAL PRESSURE FOR  
INITIAL SHOCK RADIUS.

```

DC 70 J=1,I
F(1,J)=F2(1)+PSI2(1)*(C(J)**(Q(1)+2.0)-1.0)*(F2(1)/
1PSI2(1)-B*(F2(1)+XM(1)*DCDM2(1)))/(Q(1)+2.0)
P(1,J)=F(1,J)*RH00*CO*CO*XM(1)*XM(1)/(32.2*144.)
PUNCH 91,R(1),C(J),P(1,J)
70 CCNTINUE
K=1
JJ=1
SUM=0.0
CALL FORCE(FOR,C,P,R,I,JJ,K)
DC 501 J=1,I
SUM=SUM+FOR(J)
WRITE(6,304) C(J),P(1,J),F(1,J),FOR(J)
501 CCNTINUE
TCFOR(1)=SUM

```

C  
C  
C  
C

ITERATION TO SOLVE PRESSURE, SHOCK RADIUS, SHOCK MACH  
NG. VS TIME

```

DC 80 K=2,L
TT(K)=TT(K-1)+DELT
IF (TT(K)-T0) 21,21,22
21 XM(K)=XM(1)
R(K)=R(1)
F2(K)=F2(1)
PSI2(K)=PSI2(1)
DCDM2(K)=DCDM2(1)
Q(K)= Q(1)
DO 55 J=1,I
55 P(2,J)=P(1,J)
PUNCH 92,R(K)
GC TO 80
22 X=TT(K)

```

C  
C  
C

INTERPOLATION OF INPUT DATA AND PART I DATA FOR  
VARIABLES IN PRESSURE FUNCTION

C

```

XM(K)=PIF2(X,T,M,XMS)
R(K)=PIF2(X,T,M,RS)
Y=XM(K)
F2(K)=PIF2(Y,RV,N,RF)
PSI2(K)=PIF2(Y,RV,N,RPSI)
DCDM2(K)=PIF2(Y,RV,N,RDCD)
Q(K)=3.*(PSI2(K)-1.0)
WRITE (6,301)
WRITE (6,302) TT(K),XM(K),R(K)
WRITE (6,303)
DC 90 J=1,I
F(2,J)=F2(K)+PSI2(K)*(C(J)**(Q(K)+2.0)-1.0)*(F2(K)/
1 PSI2(K)-B*(F2(K)+XM(K)*DDDM2(K)))/(Q(K)+2.0)
P(2,J)=F(2,J)*RHOC*CO*CO*XM(K)*XM(K)/(32.2*144.)
PUNCH S1,R(K),C(J),P(2,J)
90 CONTINUE
JJ=2
SUM=0.0
CALL FORCE(FGR,C,P,R,I,JJ,K)
DC 502 J=1,I
SUM=SUM+FGR(J)
WRITE (6,304) C(J),P(2,J),F(2,J),FCR(J)
502 CONTINUE
TCFCR(K)=SUM
80 CONTINUE
WRITE(6,305)
CALL CONVER(R,XM,TCFCR,TT,L)
91 FORMAT (3E15.5)
92 FORMAT (1E15.5)
301 FORMAT (1H,/,36X,'TIME',17X,'MACT',17X,'RADIUS' )
302 FORMAT (29X,3E20.7)
303 FORMAT (1H,/,39X,'R/RS',17X,'P',17X,'F',15X,'FORCE')
304 FORMAT (29X,4E20.7)
305 FORMAT (1H,/,36X,'TIME',17X,'VELC',17X,'RADCLIS',17X,'T
1CFORCE')
END

```

C  
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C

```

FUNCTION PIF2 (X,XLIST,N,FLIST)
SECOND ORDER INTERPOLATION
DIMENSION XLIST (100), FLIST (100)
BLIF (P,Q,R,S,T) = ((Q-P)*(S-T)/(R-Q)+S)
IF (X-XLIST(N)) 2,1,1
1 I = N-1
GO TO 5
2 IF(X-XLIST(1)) 4,4,6
4 I = 1
5 K = 1
GO TO 30
6 K = 2
7 DO 8 I = 1,N
IF (X-XLIST(I)) 9,9,8
8 CONTINUE
I=N
9 I = I-1
30 BLIF1 = BLIF(X,XLIST(I),XLIST(I+1),FLIST(I),FLIST(I+1)
1)
10 IF (K-1) 11,11,12
11 PIF2 = BLIF1
RETURN
12 IF((I+2)-N) 13,13,16
13 IF ((I-1)-1) 15,14,14
14 IF(ABS(XLIST(I-1)-X)-ABS(XLIST(I+2)-X))16,15,15
15 L = I+2
GO TO 17
16 L = I-1
17 BLIF2 = BLIF (X,XLIST(I),XLIST(L),FLIST(I),FLIST(L))
PIF2 = BLIF (X,XLIST(I+1),XLIST(L),BLIF1,BLIF2)
18 RETURN
END

```



```

140 FCR(N)=(.5*(P(2,N)-P(2,N-1))+P(2,N-1))*3.1416*(C(N)
1 *C(N)-C(N-1)*C(N-1))*R(K)*R(K)
GC TO 20
141 IF(RHRS-C(N)) 142,143,143
142 PH=S*(RHRS-C(N-1))+P(2,N-1)
FCR(N)=(.5*(P(2,N)-PH)+PH)*3.1416*(C(N)*C(N)-RHRS
1 *RHRS)*R(K)*R(K)
GC TO 20
143 FCR(N)=0.0
20 CONTINUE
25 RETURN
END
SUBROUTINE CONVER(R,XM,TOFOR,TT,L)

```

C  
C  
C  
C

```

THIS SUBROUTINE CONVERTS VELOCITY AND RADIUS
TO KM/SEC AND CM RESPECTIVELY

DIMENSION R(300),XM(300),TOFOR(300),CONRS(300),SHOCV(
1300),TT(300)
DC 510 II=1,L
CONRS(II)=R(II)*2.54
SHOCV(II)=XM(II)*4.9/3.281
WRITE(6,520) TT(II),SHOCV(II),CONRS(II),TCFCR(II)
520 FORMAT(29X,4E20.7)
510 CONTINUE
RETURN
END

```

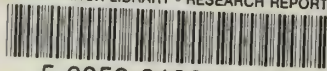
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